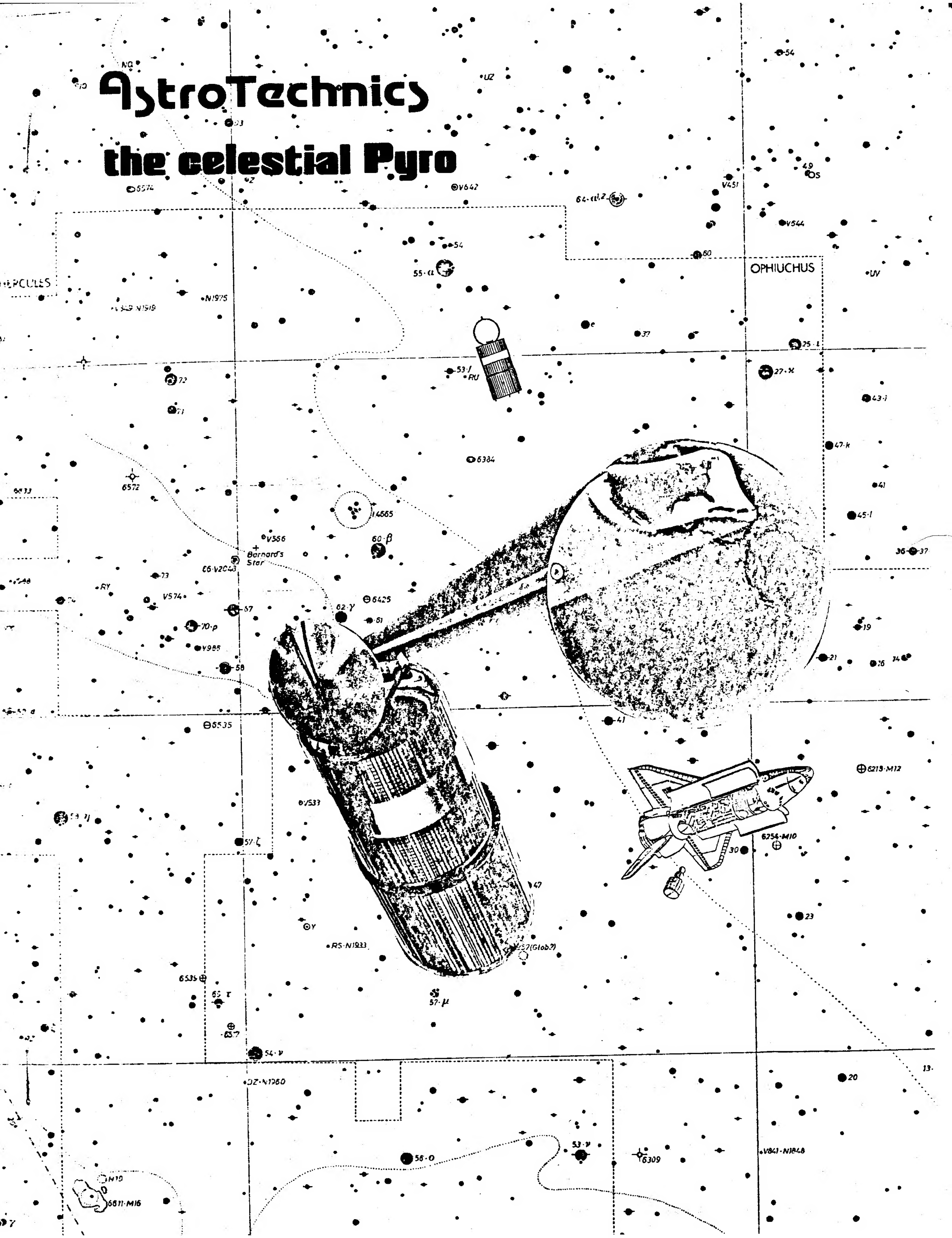
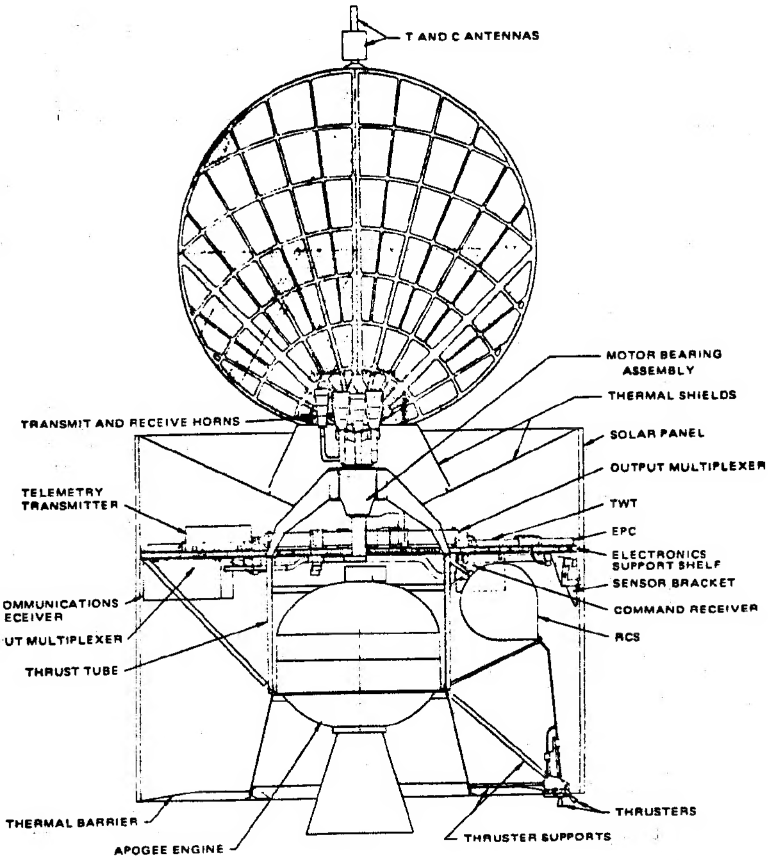
AstroTechnics

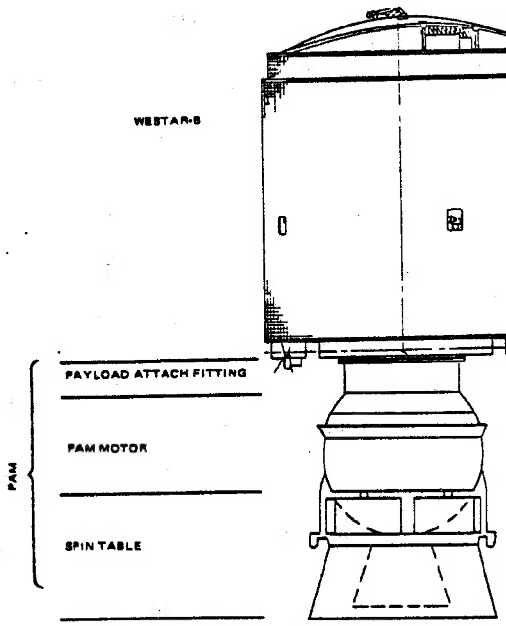
the celestial Pyro



A TOWER THRICE AS TALL AS THE WORLD *



inside an HS-333



DELTA/PAM SYSTEM

Why not one *big* tower?

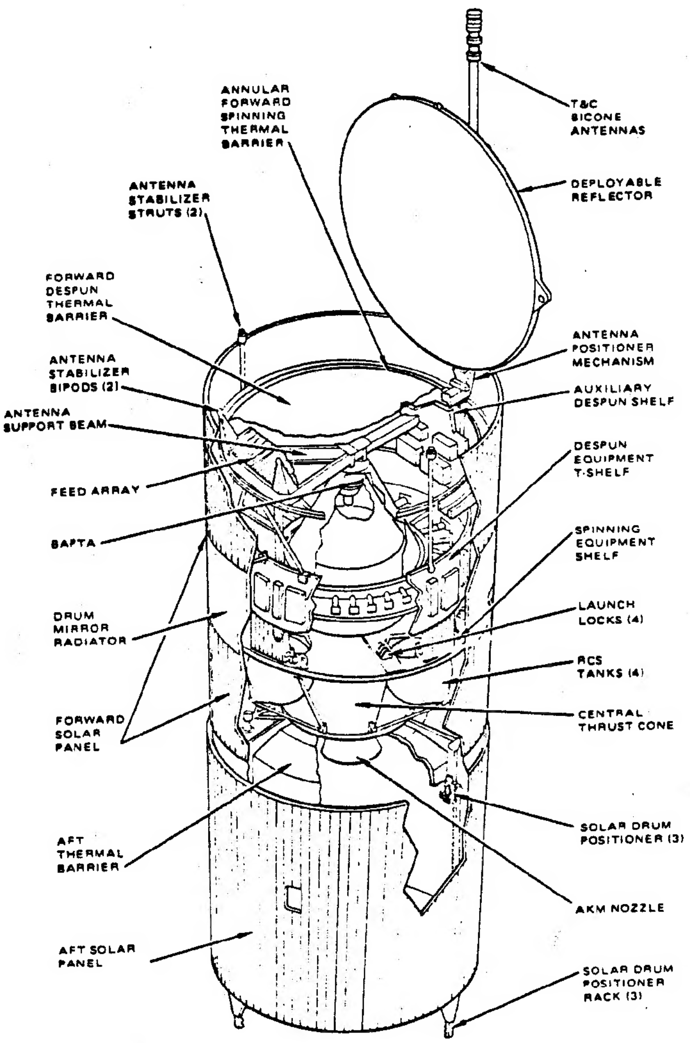
A great deal of modern telecommunications employs carriers with wavelengths between 2.5 and 30 cm., which lie in the so-called microwave region of the electromagnetic spectrum. Electromagnetic radiation at these wavelengths is virtually unaffected by atmospheric characteristics, so such signals travel in essentially straight lines. The path between transmitter and receiver must therefore be along a "line-of-sight." Before the 1960's, it was necessary to provide such communications links by the construction of microwave repeater towers. To connect the cities of the United States in this fashion entailed the erection of hundreds of such towers.

With the emergence of sufficiently powerful rocket boosters, it became possible to lift small payloads to a geosynchronous altitude. A single satellite at that height would appear to hover about a specific longitude of the Earth. By sending a microwave signal to that satellite along a line-of-sight into the sky, the satellite could amplify the signal and re-transmit it back down to Earth, blanketing the entire country at once; anyone with proper receiving equipment and tracking capability on their antenna could tap into that signal. If the satellite's orbit were always over the Earth's Equator as well, the spacecraft would appear to be fixed at a particular point on the sky; inexpensive, fixed parabolic antennas could be aimed at that location and always be assured of receiving the satellite's transmissions. This type of geosynchronous orbit is called geostationary. Arthur C. Clarke realized this and described a possible network of geostationary satellites in a paper he wrote in the 1930's for what was then the British Rocket Society (now the British Interplanetary Society). The geosynchronous altitude is unofficially called the "Clarke orbit." The first geosynchronous spacecraft, Syncom II, reached its station in 1963. Now, twenty years later, nearly 150 satellites crowd various arcs of the orbit; that number may double by the turn of the century.

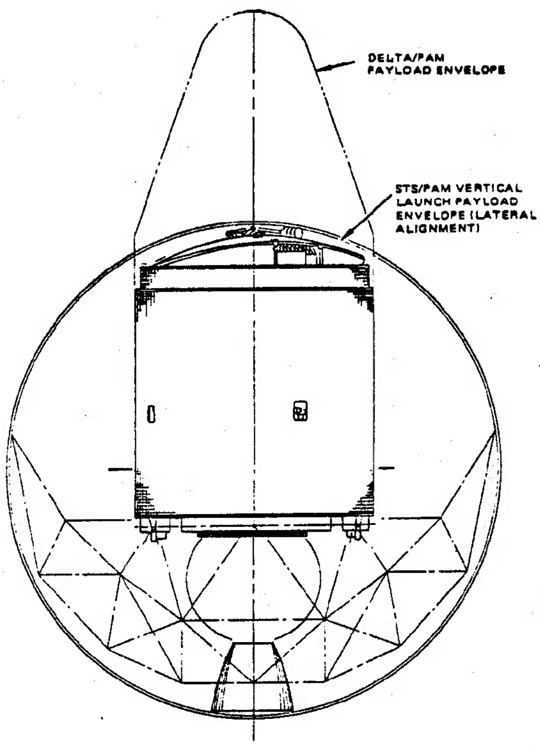
At Western Union, we use cylindrical, spin-stabilized satellites which were designed by Hughes Aircraft Corporation. The first three Westars are of a now discontinued design known as HS-333. They stand 3.45 m. (136.0") high, including the antenna, are 1.91 m. (75.1") across, and mass 297 kg. (655 lb.) when first placed on station, including 64.6 kg. (142.5 lb.) of fuel. The solar panels can generate 307 W. at the beginning of operations. The spacecraft are designed for a nominal lifetime of 7 years. Our next three satellites are of a presently widely-used design called HS-376. These are 6.59 m. (259.6") from end to end, are 2.17 m. (85.25") wide, and have a mass of 583 kg. (1285 lb.) initially, including 148 kg. (326 lb.) of hydrazine. Since these satellites carry 24 communications transponders, as opposed to 12 each on the HS-333s, their solar panels are designed to generate 917 W. at the start of their nominal 10-year lifetimes. In fact, that makes the cylindrical panels so large that the fully-extended satellites cannot be carried by existing launch vehicles; hence, half of the solar panel is built onto a hollow sleeve which slides up over the main body of the spacecraft for placement aboard the launch vehicle. Further information on the Westar satellites themselves is tabulated below.

	launch date	launch vehicle	present location
Westar-I	13 Apr. 1974	Thor-Delta 2914	retired from service 18 Apr. 1983
-II	10 Oct. 1974	"	79° West long. (to be retired in Spring of 1984)
-III	10 Aug. 1979	"	91° West
-IV	26 Feb. 1982	Thor-Delta 3910 plus PAM-D	99° West
-V	9 June 1982	"	123° West
-VI	Jan. 1984	STS-11 plus PAM-D	Los Angeles (will be placed at 91° West)
-VII	Sept. 1985	STS-30 plus PAM-D	paper

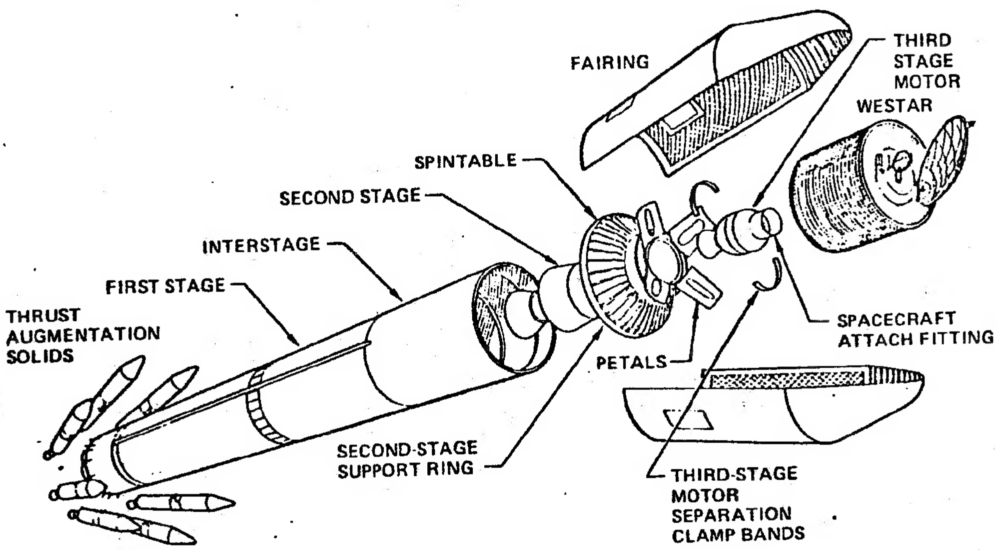
***OR: Everything but the kitchen geosynch**



inside an HS-376



the satellite stowed in a booster's nose or the Shuttle's bay



aboard a Delta vehicle

Where'd'ya wan' it, Mac?

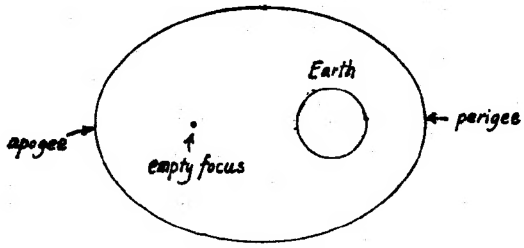
To determine where the geosynchronous circle lies, we'll need to look for a bit at the relevant physical laws. The most fundamental laws of orbital mechanics were first enunciated by Johannes Kepler during the first two decades of the 17th Century. We shall concern ourselves chiefly with the first and last of his three Laws.

Kepler's First Law states that an orbiting body follows an elliptical path lying in a plane, with the center of the gravitating body at one focus of the ellipse. A circle is the simplest possible ellipse: both of its foci are identical with the center of the circle. A satellite in a circular orbit would thus always be at a constant distance from the Earth's center (or, at a constant altitude above its surface).

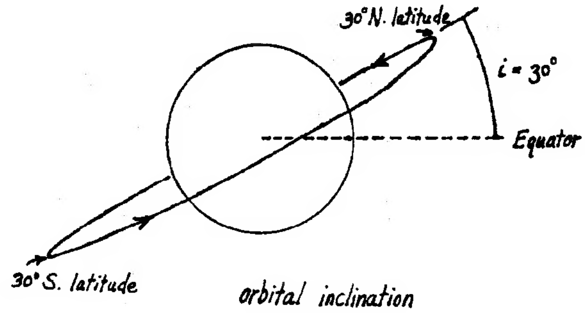
Without describing the Second Law in detail, we will simply say that it deals with the speed of the orbiting body: that body will move fastest when it is closest to the gravitating body and will move slowest when it is farthest away. One can conclude from this that an object in a *circular* orbit would travel at a constant speed.

Since the orbit of an artificial satellite lies in a plane passing through the Earth's center, if that plane is tilted with respect to the Equator, then the satellite will migrate northward and southward from the Equator in the course of its orbit. For example, if the orbital plane is inclined by 30° to the Equator (or, it is said that the *orbital inclination* is 30°), then the satellite will travel in latitude from 30° North to 30° South during a single orbit. The satellite would cross the Equator once every *half*-orbit. If the orbital plane lay in the plane of the Equator (the orbital inclination is 0°), then the satellite would *always* be over the Equator.

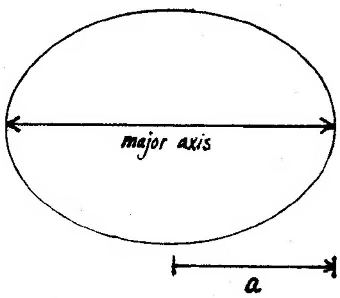
In order for a satellite to be geosynchronous, it must travel in an orbit which takes exactly the same amount of time to complete as the Earth requires to complete one rotation. This interval is known as a *sidereal day*, which is 23 hours 56 minutes 4.091 seconds long. By maintaining such a pace, the satellite would return to the same place over the Earth's Equator twice a sidereal day (since it crosses the Equator twice each orbit). If the satellite's orbit were in the plane of the Equator, the spacecraft would have the special property that it would *always* be over the *same* point on the Equator. Such an orbit is called *equatorial geosynchronous* or, simply, *geostationary*.



a Keplerian ellipse



orbital inclination



Standing still at two miles a second

To figure out how far out the geosynchronous ring lies, we will need Kepler's Third Law. This states that, if a is the semi-major axis of the orbital ellipse and P is the time required to complete an orbit (the *orbital period*), then a^3 is proportional to P^2 (this is derived elsewhere).

We can get a rough idea of how far away geosynchronous satellites belong by comparing their orbits to that of the Moon. The satellite has a period of 1 day, while the Moon's period is about 27 days. We can then write

$$\frac{P_{sat}}{P_{Moon}} = \frac{1}{27}\,, \text{ or}$$

$$\frac{P^2_{sat}}{P^2_{Moon}} = \left(\frac{1}{27}\right)^2 = \frac{a^3_{sat}}{a^3_{Moon}}\;;$$

but,

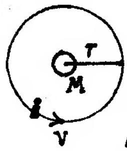
$$\left(\frac{1}{27}\right)^2 = \left(\frac{1}{3}\right)^3 \times \left(\frac{1}{3}\right)^3 = \left(\frac{1}{3}\right)^6 = \left(\frac{1}{3}\right)^2 \times \left(\frac{1}{3}\right)^2 \times \left(\frac{1}{3}\right)^2 = \left(\frac{1}{9}\right)^3,$$

so,

$$\frac{a^3_{sat}}{a^3_{Moon}} = \left(\frac{1}{9}\right)^3 \quad \text{or} \quad \frac{a_{sat}}{a_{Moon}} = \frac{1}{9}\,.$$

Geosynchronous satellites lie one-ninth of the way to the Moon. Since the orbit of the Moon, on the average, is about 40 Earth radii from Earth's center, the radius of the geosynchronous ring is about (40/9) or 6⅔ times the Earth's radius.

Kepler's Third Law



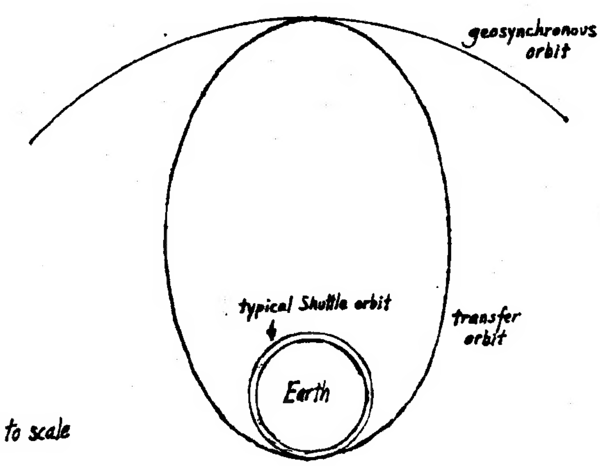
Consider a small satellite moving with speed v in a circular orbit of radius r around a planet of mass M. If the orbital period is P, then, since the circumference of the orbit is $2\pi r$, the speed is $v = \frac{2\pi r}{P}$. The acceleration needed to keep the satellite moving in a circle is $a = v^2/r$; Newton argued that gravity provided this acceleration and showed that $a = \frac{GM}{r^2}$, G being a physical constant. If we put this all together, we have

$$\frac{GM}{r^2} = \frac{v^2}{r} = \frac{\left(\frac{2\pi r}{P}\right)^2}{r} = \frac{4\pi^2 r}{P^2} \quad \text{or} \quad P^2 = \left(\frac{4\pi^2}{GM}\right) r^3.$$

That is Kepler's Third Law; the constant of proportionality depends only on the mass of the planet. Newton invented the calculus to prove that this relation holds for __any__ elliptical orbit, where the speed and the distance from the planet are __not__ constant.

If we use this result in the speed equation above, we learn that the speed of a body in a circular orbit is

$$V_{circ} = \frac{2\pi r}{\sqrt{\frac{4\pi^2}{GM} r^3}} = \sqrt{\frac{4\pi^2 r^2 GM}{4\pi^2 r^3}} = \sqrt{\frac{GM}{r}}\,.$$



Isaac Newton was able to extend Kepler's Laws into a more general system of orbital mechanics in the 1660's. His generalization provides a way of computing the precise distance to the geosynchronous ring if the mass of the Earth is known.

We can find from this that a geosynchronous orbit lies 42,164 km. (or 26,199 statute miles or 22,767 nautical miles or 6.61073 Earth radii) from the Earth's center; it is at an altitude of 35,786 km. (or 22,236 statute miles or 19,323 nautical miles). Now that we know both the size and the period of such an orbit, we can work out the orbital circumference and thus find the satellite's speed: it is 3.075 km./sec. (or 10,088 ft./sec. or 6878 mph).

(I confess that it looks like I went a bit conversion-crazy in the last paragraph. In this line of work, though, one does run across just about all of these systems of measurement. I will tend to stick to the metric one, since it is the scientific (and, soon, world-wide) system of choice.)

Erecting the tower

Today, there are three main options for launching a commercial geosynchronous spacecraft belonging to the Western nations. One is through the use of an expendable booster, usually a Delta, launched from Cape Canaveral, Florida (latitude: 28°5 N.). Another is to launch with an expendable Ariane vehicle from the Arianespace facility at Kourou, French Guiana (latitude: 4° N.). The third is to use a solid-fuel-propelled Payload Assist Module released from the cargo bay of a Space Shuttle orbiter. (Occasionally, a commercial satellite may also be launched from Vandenburg Air Force Base in California.)

Whether the satellite is launched from the ground or from the Shuttle, it is first placed by its attached Payload Assist Module into an elliptical *transfer* orbit. The *perigee* (or nearest point to the Earth) of the orbit is typically about 180 km. in altitude and the *apogee* (or farthest point from Earth) is within a few hundred kilometers of the geosynchronous altitude. The orbital inclination will be at least the same as the latitude of the original launch site, e.g., a launch from Kennedy Space Center or the Shuttle will give the transfer orbit an inclination of at least 28°5. The period of the orbit is about 10½ hours: as seen from the ground, each successive apogee occurs about 158° to the west of the previous one, as the Earth rotates under the satellite.

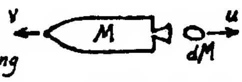
Getting into the transfer orbit is the biggest step. Starting from the surface of the Earth, the satellite has to be accelerated to a speed of 10.42 km./sec. in order to send it soaring up to the geosynchronous ring before falling back. This is not much less than the escape velocity of the Earth, 11.17 km./sec. Consequently, the vast majority of the fuel for the mission is expended in achieving this orbit. Just how much fuel that is can be estimated by the use of the ideal Rocket Equation (which is derived below); since the equation assumes a massless rocket structure, the result obtained is a lower limit for the fuel requirement. The rotating Earth helps out a little: the original launch sites are not actually stationary, but are carried toward the East at a speed of 0.465 km./sec. x cos ℓ, where ℓ is the latitude of the site. The resulting ΔV (*delta*-vee, or change in velocity) for Cape Canaveral and for Kourou are tabulated, along with the ratio of the mass of everything at launch to the mass in transfer orbit.

Just before the Payload Assist Module is fired, a small rocket-powered spin table is used to whirl the satellite about its vertical axis. A spin speed of about 90 rpm is attained for an HS-333 and of about 50 rpm for an HS-376. This table is mounted on the third stage of an expendable launch vehicle or at the base of the sun-shaded enclosure aboard the Shuttle.

The semi-major axis of an orbit is fairly simply related to the orbit's total energy: to make the orbit of the satellite larger, we must apply more energy to the spacecraft. The next step is to increase the semi-major axis from about 3.81 Earth radii for the transfer orbit to about 6.61 Earth radii for a nearly geosynchronous orbit. The most efficient way to change the semi-major axis is to cause a change of velocity at perigee or apogee (i.e., at one of the two *apses*). Since we will want to raise the perigee from 180 km. in altitude to the geosynchronous level, we will need to increase the satellite's velocity at an apogee. For this purpose, the body of the spacecraft contains another solid-fuel rocket known as the Apogee Kick Motor.

There are two other major considerations here. One is that we would like the satellite ultimately to reach a particular longitude, but the spacecraft won't necessarily reach

The Ideal Rocket Equation



A rocket functions by expelling a portion of its mass into space in a particular direction, causing the rocket to gain speed in the opposite direction. This is in accord with Newton's Second Law ("action-vs.-reaction"), also known as the law of conservation of linear momentum. This states that, in the absence of outside forces, the sum of the momenta of all the parts of a system is constant; linear momentum is just the mass of an object times its velocity.

Consider a rocket of mass M moving with speed V: it ejects an infinitesimal mass, dM, with exhaust velocity u, increasing the rocket's speed to $v+dv$. Since the linear momentum of rocket and exhaust is always constant, the changes must cancel out; hence,

$$M\,dv - u\,dM = 0 \quad \text{or} \quad dv = u\,\frac{dM}{M}.$$

This is a differential equation which can tell us how the rocket's speed changes as it gives up mass which leaves at a constant speed. If we look at the rocket from an initial time, when it has velocity v_i and mass M_i, to a final time, when it then has velocity v_f and mass M_f, then, by integration

$$\int_{v_i}^{v_f} dv = u\int_{M_i}^{M_f}\frac{dM}{M} \quad \text{or} \quad v_f - v_i = \Delta V = u\,\ln\left(\frac{M_f}{M_i}\right),$$

ln being the natural logarithm.

Rearranging this gives us

$$\frac{M_f}{M_i} = e^{(\Delta V/u)}, \text{ where } e = 2.718\ldots$$

The ideal rocket equation shows that a rocket's fuel consumption increases exponentially with the size of the velocity change and decreases exponentially with the velocity of the exhaust. Suppose a rocket, in making a certain speed change, has ¼ the mass that it started with. To make twice that change, the rocket would be left with 1/16 its initial mass. For the original speed change, if the exhaust velocity could be doubled, the rocket's final mass would be ½ of what it began with. Plainly, the goal of astronautical engineers is to obtain the highest possible exhaust velocity from a rocket and to perform a mission with the smallest possible total velocity change.

apogee just there. We cannot wait through a lot of orbits for the right point to come up, either. Since none of the onboard communications equipment is turned on yet, there is not enough waste heat to warm the interior of the satellite; hence, the longer it spends in transfer orbit, the colder everything gets. If too many transfer orbits are allowed to pass, the Kick Motor could shatter when it is fired -- an uncontrolled solid-fuel rocket can act like a bomb. (Indeed, there are a few historical incidents of losing satellites this way.) Generally, the satellite will be taken out of transfer orbit by the ninth apogee passage, less than four days after launch.

The other matter at hand is that the satellite is intended to be geostationary, which means, of course, that the orbit must be equatorial: the orbital inclination has to be reduced to zero. The most effective way to change the inclination of an orbit is to cause a change of velocity when the satellite crosses over the Earth's Equator. The two points in the orbit where this occurs are called the *orbital nodes*. This arrangements for the boost become a bit complicated, then, since the nodes of an orbit do not necessarily lie at the apses, the apogee kick maneuver *must* be done at an apogee, that apogee should be close to the final station, *and* one cannot wait too long after launch. What is done is that the launch with the booster or the release from the Shuttle orbiter is contrived so that the nodes *will* lie within a couple degrees of the apses for the particular circuit of the transfer orbit when the "kick" will be performed.

As the satellite travels along the transfer orbit, it has to dive into the outer atmosphere about every 10½ hours, attaining a speed of around 23,000 mph. The small station-keeping thrusters are used to orient the satellite so that it faces antenna-first along the orbit; the spacecraft can easily tolerate the small amount of frictional heating at 180 km. up. As the satellite approaches the last transfer apogee, it is swung around to a direction such that the Kick Motor will simultaneously increase the velocity along the orbit and bring the orbital plane toward the Equator. At apogee, the satellite is moving at 1.58 km./sec. at the inclination angle to the Equator; it must be accelerated to a speed of 3.08 km./sec. along the Equator. The total ΔV is the third leg of the vector triangle shown; the results for the different launch sites are again tabulated. Some advantage is gained from a launch site close to the Equator, partly from the greater linear speed of the Earth's surface there, but mostly because less orbital inclination needs to be removed.

The spacecraft will now be in a roughly equatorial (i < 0°3), nearly circular *drift orbit*, generally within 30° of its intended station. At this point, the spin axis of the satellite is aimed toward the North Celestial Pole (near Polaris), the solar panel and antenna are unfolded on an HS-376, and the transponders are activated. If it were desired to leave the satellite drifting eastward toward its station, the semi-major axis of the drift orbit would be set up to be *smaller* than that for a geosynchronous orbit. This makes the orbital period *less* than a sidereal day, so the satellite *gains* on the Earth's eastward rotation. To bring about a westward drift, the semi-major axis is made larger than geosynchronous, so the orbital period will be *longer* than one day.

As the drift orbit brings the satellite nearer to its final station, the drift rate must be reduced. As we have discussed previously, the orbit is best adjusted at perigee or apogee, so such changes can only be made *at most* once every half-orbit or about every 12 hours. Any remaining inclination must also be removed. The final orbit will have a remaining drift rate of less than 0°01 per day, an orbital inclination of only a few hundredths of a degree, and a difference in altitude between perigee and apogee of only a few miles.

These last corrections can only be made with the small station-keeping thrusters and the available hydrazine aboard the satellite; all other means have now been exhausted. There are two thrusters pointed parallel to the axis of the cylinder, called the *axial thrusters*, and two at right angles to the axis, called the *radial thrusters*. The radial thrusters correct the drift rate by firing along a tangent to the orbit. The axial thrusters change the orbital inclination by firing at right angles to the plane of the orbit. Since these latter thrusters point "down" toward the South Celestial Pole, they can only push "up" on the orbital plane; hence, the inclination maneuvers can only be done at most *once* a day at the *descending node* of the orbit, when the spacecraft is crossing the Equator from North to South.

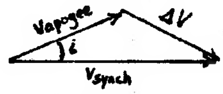
When the final orbit is achieved, the satellite's microwave repeaters stand at the top of an imaginary twenty-two-thousand-mile "tower" over an assigned spot on the Equator. The satellite can now begin commercial operations.

The ideal rocket equation can be used to estimate the amount of fuel required to place a satellite into a nearly-geosynchronous drift orbit. Let m_d be the mass of the spacecraft in drift orbit, m_t its mass in transfer orbit, and m_ℓ its mass at launch. The exhaust velocity, u, of present-day rockets varies from about 3 km/sec (early Deltas) to 4.5 km/sec (STS). Launches from Cape Canaveral and Kourou are compared.

surface to transfer orbit:

launch from	ΔV (km/sec)	m_ℓ/m_t $u=3$	m_ℓ/m_t $u=4.5$
Kourou	9.956	27.6	9.1
Canaveral	10.011	28.1	9.3

transfer orbit to drift orbit:

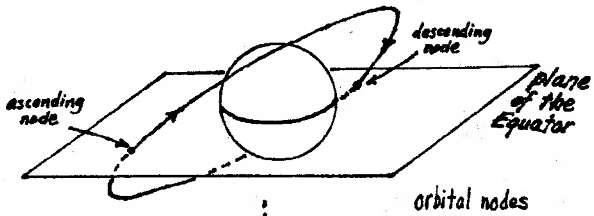


launch from	i	ΔV	m_t/m_d $u=3$	m_t/m_d $u=4.5$
Kourou	4°	1.507	1.65	1.40
Canaveral	28°5	1.850	1.85	1.51

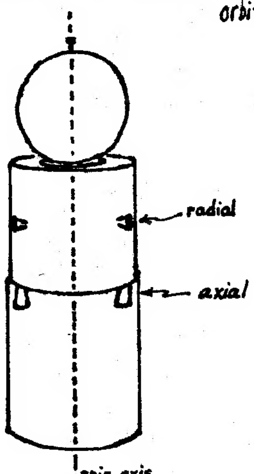
complete launch:

from	m_ℓ/m_d $u=3$	m_ℓ/m_d $u=4.5$
Kourou	45.5	12.7
Canaveral	52.0	14.0

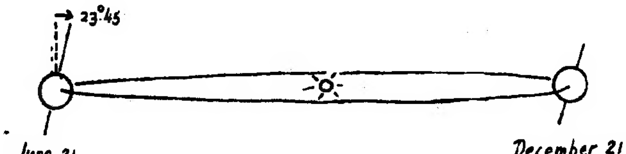
These results are lower limits for fuel consumption, since they do not consider the mass of the rocket structure itself. The advantage given by higher exhaust velocity is evident. A launch from the nearly equatorial Kourou saves about 10% over a launch from Cape Canaveral.



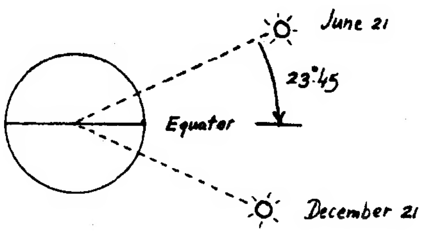
orbital nodes

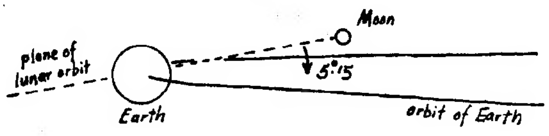


spacecraft thrusters

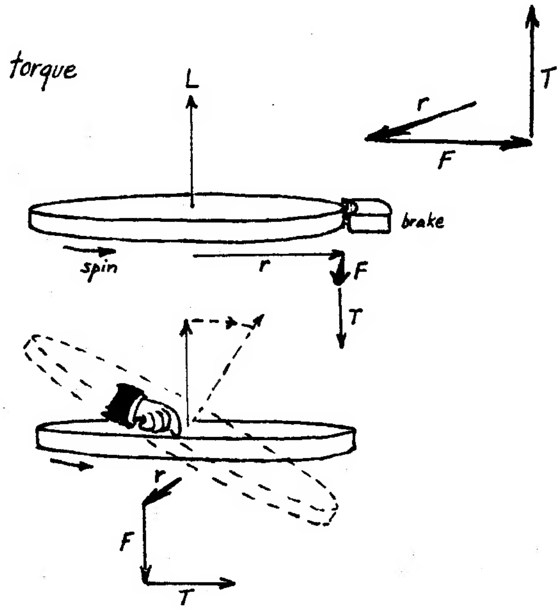


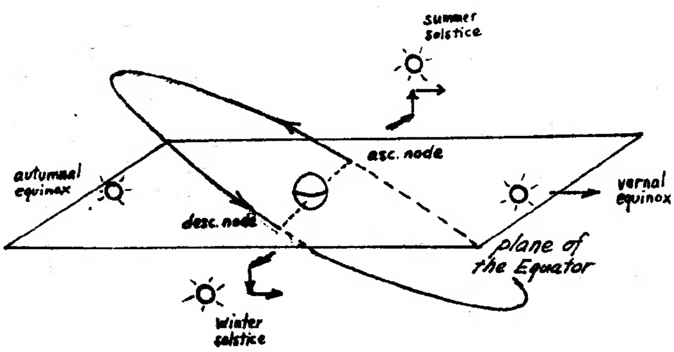
Earth's axial tilt





inclination of Moon's orbit





The tower will rock

If the Earth were alone in the Universe and it were a perfectly symmetrical sphere, then orbits around it would be precisely as Kepler predicted. In fact, our planet is a little oblate, due to its rotation, and a bit "lumpy", since it was built up from smaller bodies when it was formed. Further, every other object in the Universe exerts gravitational force on the Earth and its satellites; overwhelming all else is the action of the Sun and the Moon. We must apply Newtonian dynamics to the analysis of the satellite's actual motion, in order to reckon the departures, or *perturbations*, from the simple Keplerian orbit. These perturbations have the effect of pulling the spacecraft away from its ideal location; this necessitates the activity of *station-keeping* to counteract these natural influences.

One of the simpler perturbations has no effect on station-keeping. The gravitational influence of the Sun, the Moon, and the oblateness of the Earth serves to reduce the orbital energy of the spacecraft slightly. As a result, the satellite must be placed a little bit farther away from the Earth in order to have the proper orbital period. This effect is small: the actual radius of the geosynchronous ring is about 6.6109 Earth radii or 42,165 km.

The other perturbations we shall look at can be divided into three categories. Some affect the orbital inclination and hence the latitude range of the satellite; this effect is corrected by "north-south" station-keeping. Others draw the spacecraft away from its desired longitude and are compensated by "east-west" station-keeping. Finally, the spin axis of the satellite is constantly being pushed away from its orientation toward the North Celestial Pole; attitude station-keeping is conducted to deal with this.

We control the vertical

As the Sun and the Moon are rarely over the Equator, their gravitational attractions work to pull the satellite's orbit out of the plane of the Equator. The Sun appears to shift in latitude from 23°45 North to 23°45 South and back in the course of a year. This is due to the tilt of the Earth's axis of rotation with respect to a perpendicular to the plane of its orbit. This produces the familiar annual cycle of the seasons. The Moon's orbit is inclined about 5°15 to the plane of the Earth's orbit. The two points where the Moon passes through the Earth's orbital plane are called the nodes of the lunar orbit; the line connecting these points is the *line of nodes*. Because of perturbations acting upon the Moon in its orbit, this line of nodes does not retain a fixed direction in space, but slowly rotates, completing a circle in about 18.6 years.

A body rotating on its own axis, or revolving about a central point, has a physical quantity associated with it, called *angular momentum*; briefly, it is proportional to the product of the speed of rotation and the size of the spinning body or of the orbit. It seems to be a principle of Nature that this quantity and the direction of rotation remain constant unless a force acts on the body.

If a force, F, is applied at a distance *r* from the center of rotation, it produces a change in the angular momentum, called *torque* (T), at right angles to both the force and the line from center to point of application, in the direction shown. For example, a tire spinning counterclockwise has an angular momentum, L, as shown; a brake applied at the rim of the wheel applies a force against the spin, thus creating a torque in the direction opposite to L. So the angular momentum is reduced and the tire slows in its rotation. On the other hand, if you push *down* on the spinning wheel, the torque, again at right angles, will not change the speed but instead the direction of rotation, causing the wheel to heel over to one side. We will see a couple of manifestations of this behavior further along.

If we refer to the Earth's Equatorial plane (the plane of the satellites' orbits), the Sun seems to circle the Earth annually in an orbit inclined about 23½°, crossing from South to North at the Vernal Equinox on March 21, reaching a northerly peak at the Summer Solstice on June 21, crossing from North to South at the Autumnal Equinox on September 23, passing to its southernmost point at the Winter Solstice on December 21, and returning to the Vernal Equinox. The Sun thus pulls up on the satellite from one side for half the year and down from the other side for six months. The torque consequently pulls the angular momentum toward the Vernal Equinox all year: the satellite's orbit tends to lean over, creating an ascending node near the Summer Solstice and a descending node in the vicinity of the Winter Solstice. Because of the varying angle of the Sun from the Equator, there is a seasonal variation in the rate at which the orbit tilts, being greatest in June and December and least in March and September.

The action of the Moon complicates this slightly. When the descending node of the lunar orbit is lined up with the Vernal Equinox, the Moon's variation in latitude is minimal, shifting from 18°3 North to 18°3 South in the course of a month. The added torque due to the Moon is thus also minimal at that time. That was the physical situation which occurred in 1978. In a bit over nine years, the Moon's line of nodes will rotate to bring the ascending node into alignment with the Vernal Equinox. The monthly swing in the latitude of the Moon becomes maximal, shifting from 28°6 North to 28°6 South and back; the Moon then makes its strongest contribution to the torque acting on the satellite. This will be the case during 1987.

The rate of build-up of the spacecraft's orbital inclination can be over 0°12 per month. Since the FCC requires the orbital inclination to remain less than 0°1, we perform a corrective maneuver every four weeks. Recall that the axial thrusters, which are needed for this purpose, are on the bottom of the satellite, so they can only push up on the orbit. The most effective points from which to alter the inclination are the orbital nodes, so we must fire these thrusters when the satellite reaches its descending node. We wish to swing the velocity of the satellite so that the descending node becomes an ascending node, thereby counteracting the natural behavior. An average inclination maneuver turns the velocity through an angle of about 0°075, so a ΔV of 3.075 km./sec. x sin 0°075 = 4.0 m/sec. (= 13 ft./sec.) is required; the actual amounts vary from 3 to 5 m./sec. every six months. Maintenance of inclination proves to be the most expensive part of station-keeping: 95% to 97% of the on-board fuel is consumed in this cause. The annual costs in fuel are rising for all concerned. The worst season will be the summer of 1987, before the long decline in total torque down to the minimum in the spring of 1996.

The lines of orbital nodes for all geosynchronous satellites lie in roughly the same direction in space. The times at which our satellites reach their descending nodes, and hence the times for their inclination maneuvers, depend primarily on their longitudes and the time of year.

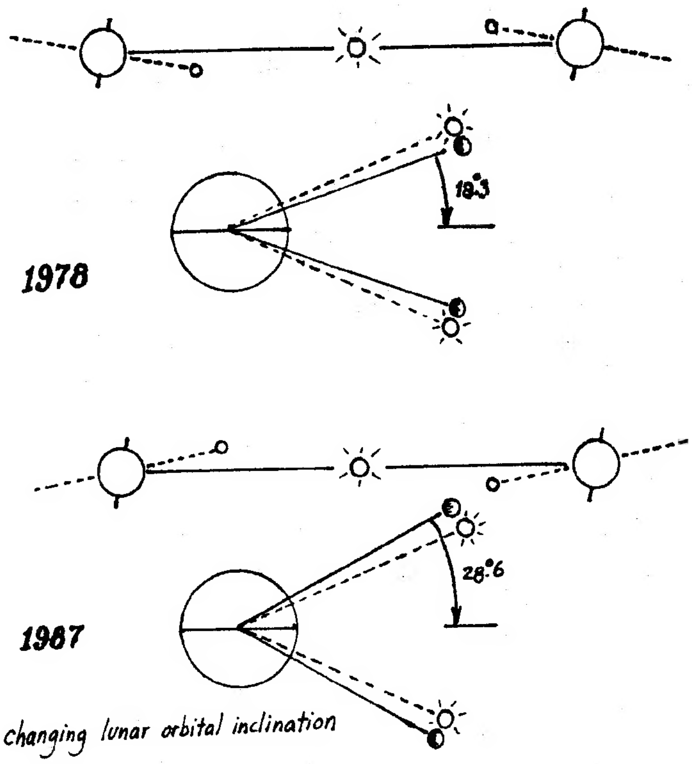
As seen from space above the Earth, all of these satellites are seen to circle the Earth at a rate of about 15° per hour or of 1° in 4 minutes. Consider the locations of our satellites: if Westar-II, at 79° West longitude, reaches its descending node at some particular moment, then Westar-III, at 91° West, reaches its descending node (91° - 79°) x 4 minutes per degree = 48 minutes later; Westar-IV, at 99° West, would be there 80 minutes after W-II; and Westar-V, at 123° West, 176 minutes later.

From the same viewpoint, the Sun seems to circle the Earth at a rate of about 30° per month. Standard Time is based upon the average apparent motion of the Sun, so that the Sun appears at its highest point in the sky around noon. The Sun is lined up with the descending node direction, near the Winter Solstice, around December 21st; in a month, it will be 30° east of that point. In December, Westar-III reaches its descending node at about 6 PM Greenwich Mean Time; a month later, when it reaches this same direction in space, the Sun will lie 30° to the east, so this event will occur about two hours earlier by the standard clock, at about 4 PM GMT in January. The time of inclination maneuvers continues to move two hours earlier each month throughout the year. This timing is highly fortuitous for us commercial satellite operators in the Western Hemisphere: the middle-of-the-night maneuvers occur in the summer and the winter maneuvers land during normal office hours! (I hope the Other Guys, with their Ekrans and Gorizonts, put *their* thrusters on *top*...)

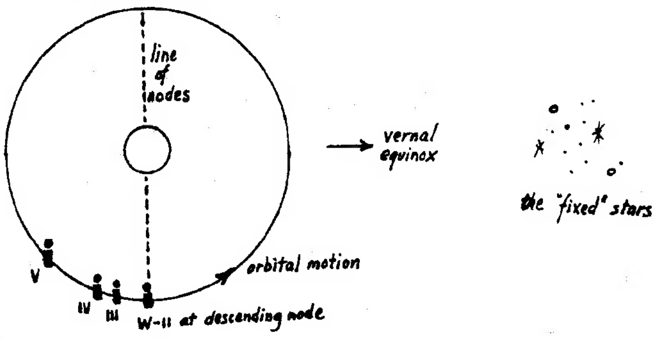
We control the horizontal

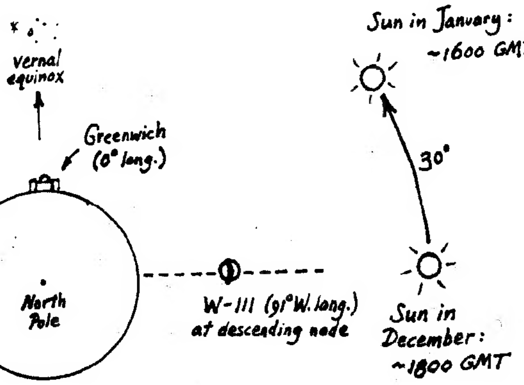
The "lumpiness" of the Earth's gravitational field also produces continual changes in a satellite's orbit. These irreg larities are quite small and, for our considerations here, can be approximated by regarding the Earth as having an elliptical Equator. The minor axis of this Equatorial ellipse passes through 105° West and 75° East longitude. The effect of this is similar to that of attaching two small masses to the equator of a sphere at the positions of 15° West and 165° East longitude.

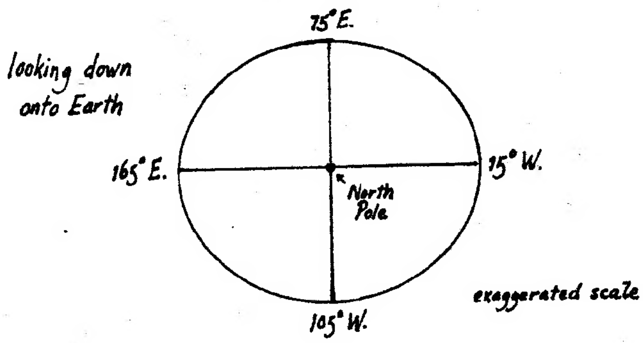
Consider a geostationary spacecraft placed at some longitude between 15° and 105° West longitude. A symmetrical sphere would allow this satellite to remain over that position indefinitely. The extra mass at 15° West (let us call it the Western Mass) pulls the satellite from the same direction as its normal eastward orbital motion around the Earth and so accelerates it. By accelerating the spacecraft, energy is added to its orbit, so the satellite moves into a higher orbit, giving it an orbital period longer than a sidereal day. The satellite thus falls behind the Earth's rotation and so "drifts" to the west. The Western Mass continues to accelerate the spacecraft, moving it into progressively higher orbits until

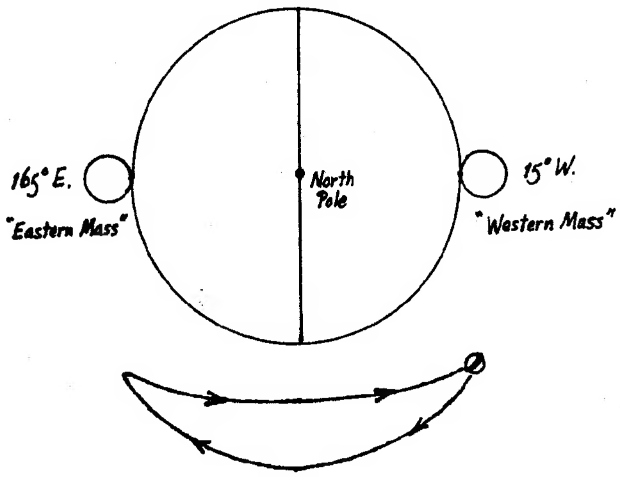


changing lunar orbital inclination

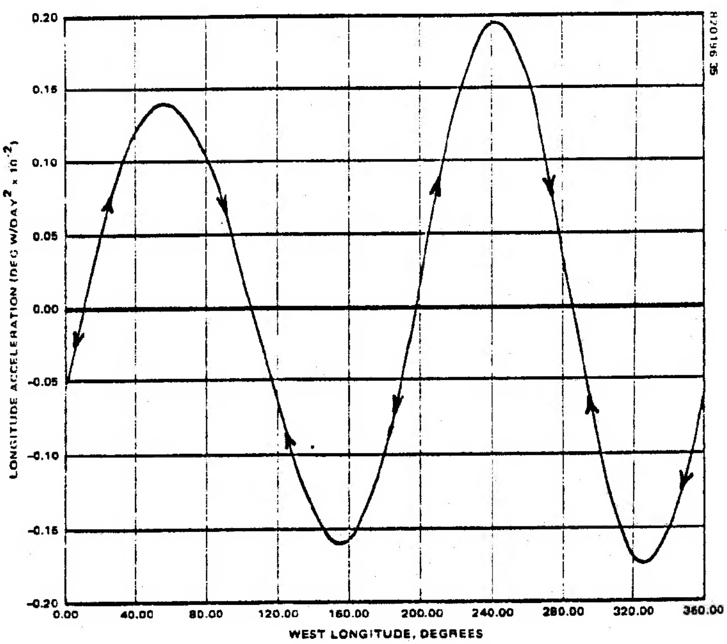


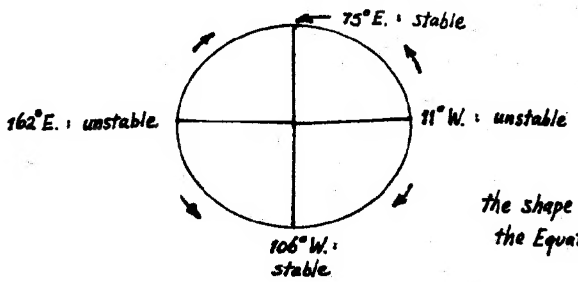






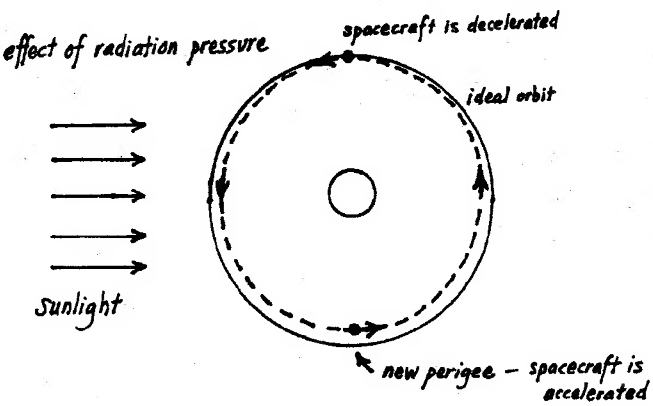
the longitudinal accelerations





the shape of the Equator

effect of radiation pressure



the satellite has drifted to 105° West. There the gravitational influence of the Western and Eastern Masses are equal, so no further acceleration occurs. However, the satellite is still drifting westward and becomes closer to the Eastern than the Western Mass. The Eastern Mass draws on the satellite from behind its normal orbital motion, thereby decelerating it. This removes energy from the orbit: the orbital period begins to catch up with the sidereal day, so the spacecraft slows in its westward drift, stops, and begins to drift eastward. The eastward drift continues as the satellite again crosses 105° West; the Western Mass then commences to boost the orbit until the spacecraft turns around at its initial longitude to repeat the cycle.

This behavior is reminiscent of that of a pendulum. A spacecraft at exactly 105° West or 75° East is analogous to the pendulum at rest: it would remain in place forever. This condition is known as *stable equilibrium* and so 105° West and 75° East are called the *stable Equatorial nodes*. A satellite at exactly 15° West or 165° East is like an inverted pendulum: without disturbance, it too would remain in place forever, but the slightest outside influence would immediately cause it to fall. That condition is an *unstable equilibrium*; 15° West and 165° East are the *unstable Equatorial nodes*. Since there are many external influences on a satellite, it would not remain at either of those positions for long. An unattended spacecraft at any other longitude would behave like a swinging pendulum: the satellite would sweep back and forth forever on an arc centered on one of the two stable nodes. In reality, the Earth's lumpiness is not exactly symmetrical. The four nodes are not 90° apart and the accelerations are not all equal in each quadrant, but the overall behavior is substantially as has been described.

The FCC requires the satellites to remain within 0°.1 of their assigned longitudes. The rate at which a satellite drifts across its "box" increases as the longitude becomes farther from a stable node. Westar-IV, which is only 7° from the node at 106° West, can be kept inside its limits unassisted for about twelve weeks, while Westar-II, being 27° away from the same node, can only do so for under five weeks. As a measure for safety and to provide regularity in operations, we perform drift-correcting maneuvers also every four weeks.

The amount of velocity change required to adjust the drift rate consequently depends on the satellite's longitude. In the course of four weeks, the greatest amount of drift rate any of our satellites build up comes to about 0°.015 per day. The corrective maneuver gives the spacecraft a roughly equal drift rate in the opposite direction; the satellite's newly-induced drift will slow, stop, and return to the natural direction, to be reversed again in four weeks. Starting from the geosynchronous altitude, to induce a drift rate of 1° per day requires a ΔV of 2.8 m./sec. (9.3 ft./sec.). An average drift maneuver will thus call for a ΔV of from 0.03 m./sec. (0.1 ft./sec.) for Westar-IV to 0.12 m./sec. (0.4 ft./sec.) for Westar-II. If we recall the average speed of these satellites, it is clear that we are speaking of changing the speed by at most a few parts in 100,000. These maneuvers use about 2% to 3% of the available on-board fuel supply. A single radial thruster is fired on a tangent to the orbit in the appropriate direction.

The timing of the drift maneuvers is determined by another effect. The pressure of sunlight, small as it is, slows the satellite as its orbital motion carries it toward the Sun and accelerates it as the spacecraft moves away. The slowing of the satellite in its orbit on the side lagging the Sun by 90° causes it to fall toward the Earth a little sooner than would have been the case otherwise. The acceleration on the side leading the Sun by 90° lifts the spacecraft into a slightly higher trajectory. The sunlight is thereby moving the orbital perigee toward a point 90° ahead of the Sun and the apogee to a place 90° behind. If this were allowed to continue, the eccentricity of the orbit would increase to an unacceptable level. The eccentricity produces a variation in the satellite's speed (remember Kepler's Second Law!); this makes the spacecraft alternately gain and lose against the Earth's rotation during each orbit. The satellite appears to perform a daily "wiggle" east and west: if left uncontrolled, the diurnal meandering would grow large enough to make the satellite leave its "box" twice a day. Therefore, the drift maneuver is performed at a point in the orbit that will bring the perigee back "behind" the Sun; at the midpoint of the four-week cycle, the perigee is then aligned with the Sun. Because the eccentricity is so tiny (the difference in altitude between apogee and perigee is one to two parts in 10,000 of the orbital semi-major axis), there is no simple seasonal relationship for the timing of the drift maneuver.

We can determine the physical size of the "box" within which we may operate the satellite. The geosynchronous circle has a circumference of $2\pi \times 42{,}165$ km. = 264,930 km., so 1° of it is 736 km. (457 mi.) long. The "FCC box" is thus 147 km. (91 mi.) square and $\leq$ 8 km. (5 mi.) thick.

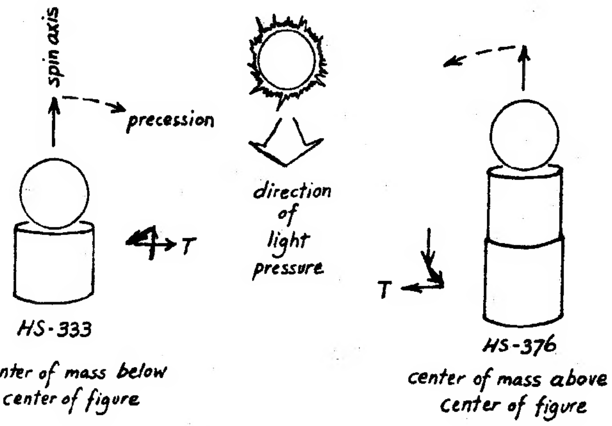
When it is decided that a satellite has reached the end of its useful life and is to be retired, it may be placed in an orbit either higher or lower than the geosynchronous level. If the satellite is given a drift rate greater than about 0°35 per day, the "pendulum effect" is overwhelmed: the satellite will continue to drift around the world in the same direction forever. This is like giving the pendulum a good hard push, setting it spinning on its pivot eternally.

A matter of attitude

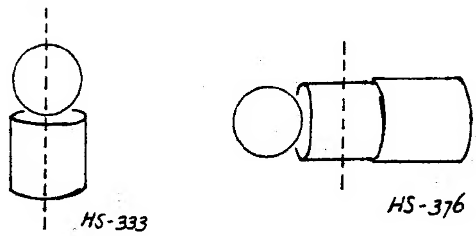
The satellite must not only be narrowly confined in space, but must be kept oriented so that its spin axis always points quite near the North Celestial Pole. This must be done in order to keep the returning amplified beam from the satellite properly centered over the United States. The constraints on the spacecraft attitude are to keep the spin axis within 0°1 of the Pole for an HS-333 and within 0°15 for an HS-376. This is important since the signal strength at the edge of the beam's "footprint" drops off quite abruptly and the size of the "footprint" isn't much larger than the size of the country.

We have already discussed angular momentum and torque. The pressure of sunlight produces a force on the spinning satellite. If the spacecraft were a symmetrical object, there would be no lever arm, so to speak, through which to apply the force: the angular momentum would be unaffected. However, the center of mass of the two types of satellites we have is *not* at the center of the geometrical figure. For an HS-333, the center of mass is slightly below the center of figure; for an HS-376, it is well above the center of figure. If the Sun and the satellites are arranged as shown, the spin axis of the HS-333 will move (or *precess*) to the right, while that of the HS-376 will precess to the left.

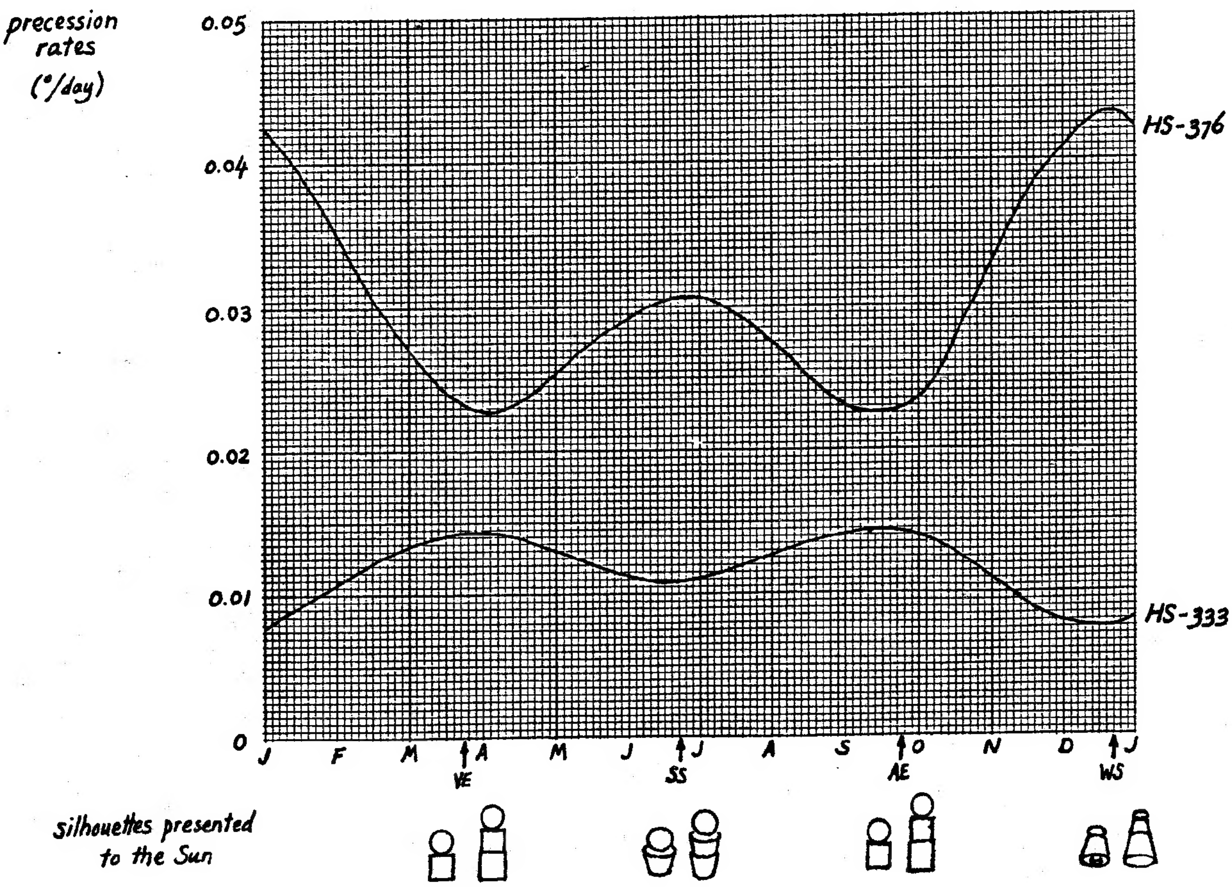
This matter is complicated by the difference in the spin stabilities of the two varieties of satellite. An HS-333 is a squat cylinder, about as wide as it is tall, with its center of mass not far from the center of its body: rotation about its axis of symmetry is very stable. The HS-376, on the other hand, is half hollow, so its center of mass is up toward the "top" end: rotation about *its* axis of symmetry is highly unstable. Such a body would far prefer to spin about an axis *diametrically* through the center of mass (a so-called *flat spin*). This sort of instability makes an HS-376 precess much faster than would be due to its greater physical size alone. It will precess through its 0°3 "attitude circle" in as little as seven days, while an HS-333 will takes 14 days or longer to precess through its 0°2 "circle".

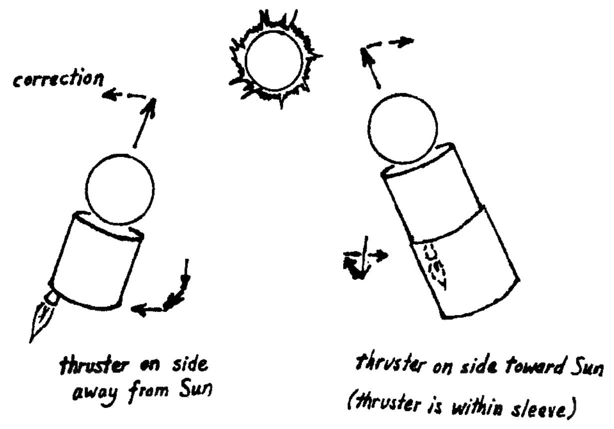


Stable Modes of Rotation

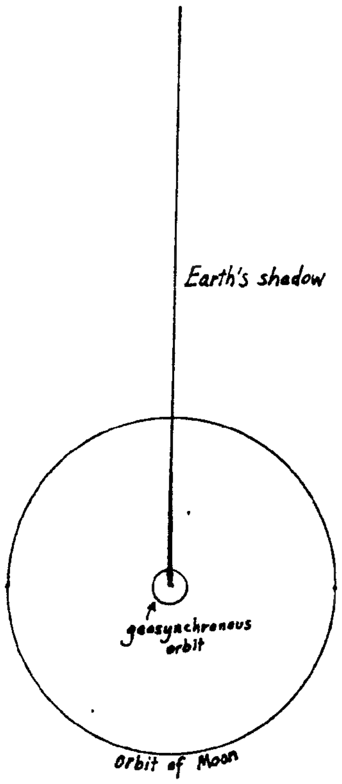


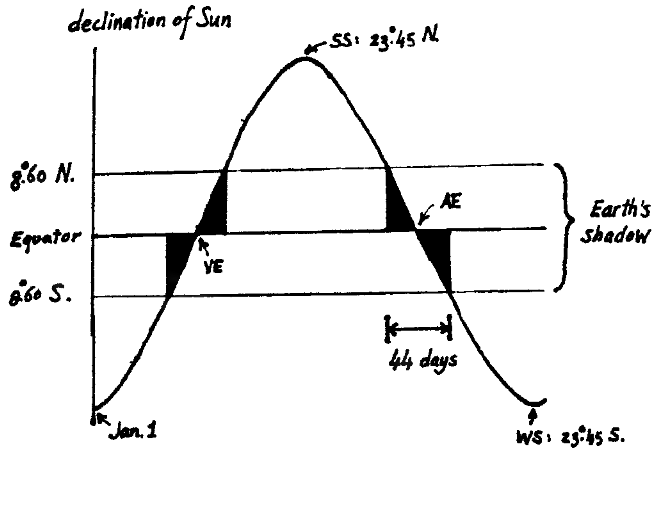
The rate of precession of the spacecraft varies with the seasons. At the Vernal and Autumnal Equinoxes, the satellites are face-on to the Sun and present the greatest possible silhouette to its light pressure; at the Summer and Winter Solstices, the light of the Sun arrives obliquely downward or upward. The precession rate will depend on the length of the lever arm produced by the distance of the center of mass from the apparent center of figure; the annual cycle is shown by the graph.





attitude maneuvers





For a corrective maneuver, one of the axial thrusters is fired. In both types of spacecraft, the axial jets are located below the center of mass at the rim of the cylinder. The lever arm thus points outward from the central axis and the force pushes upward on the satellite. Hence, as arranged in the diagram, to make the spin axis of the HS-333 move back to the left, an axial thruster must be fired when it is on the side of the spacecraft away from the Sun. For an HS-376, the spin axis must be moved to the right, so an axial jet is fired when it reaches the Sunward side. The timing of an attitude maneuver has a negligible effect on its efficiency (so we do ours on weekday afternoons!).

As the satellite consumes fuel, it loses mass, causing the effective lever arm for torque to grow longer. Consequently, the satellites gradually precess faster as they age: the precession rate curves shown will slowly slide upward on the graph. We conduct attitude maneuvers on the HS-333s every 14 days. At the beginning of their ten-year lives, we can do corrections for the HS-376s every seven days; toward the end of that time, it is expected that such maneuvers will need to be done every three or four days. Over the interval of the missions, attitude corrections consume about 1% to 2% of the station-keeping fuel.

What all of these station-keeping maneuvers have in common is that they serve to over-correct the perturbations. The maneuvers are planned to place the satellite in a condition so that halfway through each maneuver cycle it winds up where we *really* want it. This is reminiscent of the way one turns a plant growing in a pot near a window: the plant is always trying to bend in one direction, but one turns the pot every so often, so that on the average the plant grows straight.

If we add up all the velocity changes it is necessary to make for station-keeping during the life of the satellite, we can estimate the amount of on-board fuel required for the mission. Inclination corrections dominate the total: 13 such maneuvers per year, at an average of 4.0 m./sec., are performed. If these make up about 96% of the total, then the total equivalent ΔV for all maneuvers comes to (13 x 4.0 x 7 / 0.96) = 379 m./sec. for an HS-333 and (13 x 4.0 x 10 / 0.96) = 542 m./sec. for an HS-376. The propellant used for station-keeping provides an exhaust velocity of about 2 km./sec., so, referring back to the ideal Rocket Equation, we find that the ratio of mass at the start of the satellite's life to the mass with all fuel consumed is 1.21 for an HS-333 and 1.31 for an HS-376. The spacecraft have to be designed so that about 17% of the HS-333's weight and about 24% of the HS-376's weight is on-board fuel. These figures jibe pretty well with the general descriptions given at the beginning of this article.

The shadowed nodes

The communications and telemetry equipment aboard the satellite receive their power from the solar cells which cover the sides of the cylindrical body. In a geostationary orbit, however, it is inevitable that the spacecraft must sometimes pass through the Earth's shadow and, less frequently, that of the Moon. When this occurs, the circuitry must be switched over to draw upon on-board batteries. For purposes of planning and preparation, it is necessary to know when these eclipses may occur and how long they may last.

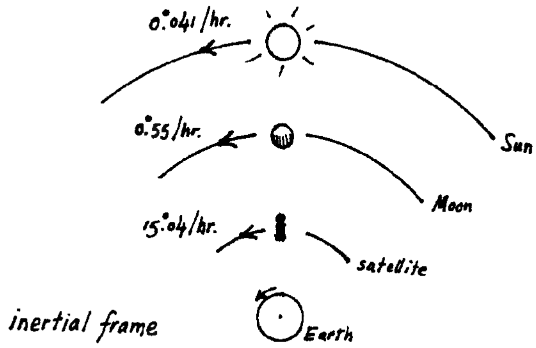
The most common eclipses are those caused by the passage of the satellite through the Earth's shadow, which extends some 1,383,000 km. (859,000 mi.) outward at those times. Most of the year, this shadow is angled above or below the plane of the Equator, so it misses the geosynchronous ring entirely. As the Sun approaches one of the Equinoxes, though, the disk of the Sun begins to be occulted by the disk of the Earth, as seen from the spacecraft. The radius of the Earth is 6378 km. (3963 mi.), so the apparent angular size of the Earth's disk is 2 x arctan (6378 km. / 42,165 km.) = 17°20 across. Eclipsing effectively begins when the center of the Sun's disk is covered. A "season" of solar eclipsing for the satellites takes place while the Sun is within 8°60 of the Equator. The angle of the Sun away from the Equator is given by a sinusoidal function with an amplitude of 23°45 and a period of one year. So the solar eclipses begin at a time of

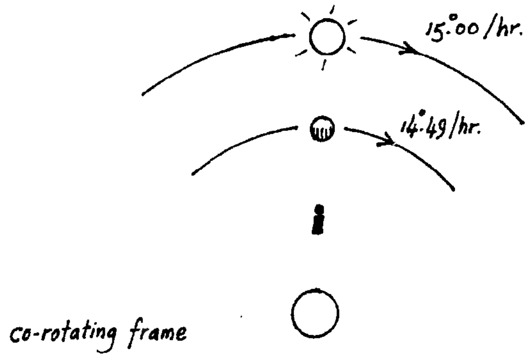
$$[\ \arcsin(8°60 / 23°45) / 360°\ ] \times 365.24 \text{ days}$$

or about 22 days before each Equinox and end about 22 days after each one; hence, the eclipses plague the satellites about twelve weeks out of the year. The longest eclipses occur on the days of the Equinoxes, when the Sun is seen to cross the diameter of the Earth's disk. Since the Sun appears to move at 15°04 per hour, the maximum duration of such an eclipse is (17°20 / 15°04) hours or about 69 minutes. To provide a safety margin, the on-board batteries are designed to supply full power for 1½ to 2 hours.

The satellites may also be adumbrated by entry into the Moon's shadow. This takes place when the Moon is close to one of the nodes of its orbit when it is aligned between the Earth and the Sun; these are the same conditions that produce a solar eclipse on the surface of the Earth. These eclipses by the Moon can happen as many as six or seven times during the year (though the average is between three and four); when a solar eclipse is occurring somewhere on Earth, it is likely that the satellites will undergo lunar eclipses that day (but these are not the only days when that is possible).

The Moon's distance from the Earth varies from 363,353 km. (225,777 mi.) to 405,648 km. (252,058 mi.) in the course of its orbit. At the time of a lunar eclipse on the satellite, the Moon lies between 321,190 and 363,480 km. from the spacecraft. The radius of the Moon is 1738 km. (1080 mi.), so the apparent angular diameter of the Moon could be from 0°620 at its perigee to 0°548 at its apogee, as seen from the satellite. From a viewpoint above the Earth, the Sun seems to circle the Earth in an easterly direction at 0°986 per day or 0°041 per hour; the Moon seems to circle in the same direction at 13°2 per day or 0°549 per hour; and the satellite also circles to the east at 15°04 per hour. If we rotate this point of view in synchrony with the Earth, the Sun is seen to travel to the west at 15°00 per hour and the Moon likewise at 14°49 per hour. Thus, the satellite would see the Sun slip behind the Moon at a relative rate of 0°51 per hour. The longest possible loss of sunlight due to an eclipse by the Moon can last from (0°548 / 0°51) to (0°620 / 0°51) hours or from 64½ to 73 minutes. This is about as long as the longest eclipses in the Earth's shadow, so similar preparations must be made here.

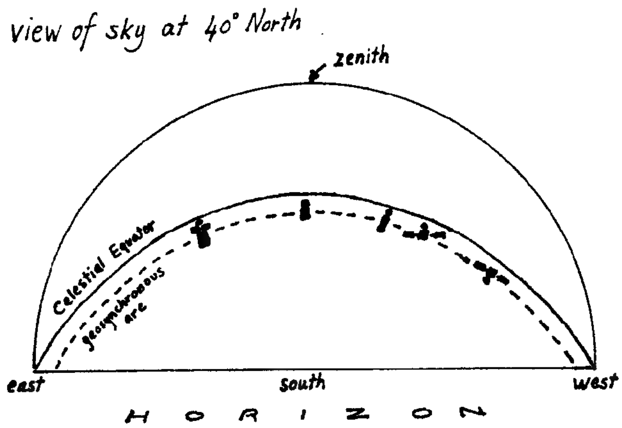




Lost it in the sun

In a geostationary orbit, it is also inevitable that the Sun must been seen to pass directly behind the satellite at some time, causing the natural radio noise of the Sun to enter the antenna beam of a ground receiving station, thereby drowning out the signals from the satellite itself. This phenomenon is called *sun interference* or a *sun outage*.

Since the satellites are not at an infinite remove, we do not see them on the sky at the Celestial Equator. From the United States, we look down slightly to the geosynchronous ring, so the spacecraft appear to lie a bit south of the Celestial Equator (from Puerto Rico, about 3° south; from Alaska, about 8° south). The Sun passes through these latitudes before reaching the Vernal Equinox and after passing the Autumnal Equinox. For our users throughout the United States and its territories, the sun interference "seasons" span February 28 to March 12 and October 1 to 13.



The duration and span of the outages at a particular station depend upon the size of its receiving antenna. It is a property of electromagnetic radiation that the apparent diameter of the Sun's "radio image" varies inversely with the diameter of the receiving dish. To the human eye, using "visible" light, the Sun appears to be about 0°53 across. To a 17-meter diameter dish using microwaves, the disk of the Sun seems to measure about 1° in diameter; to a smaller dish, the Sun looks even bigger. Recalling that the Sun appears to move westward across the sky by 1° every four minutes, we can estimate the intervals of the most severe interference:

antenna diameter	Sun's diameter	duration
17-meter	0°98	4 mins.
10-meter	1°23	5 mins.
3-meter	3°0	12 mins.

This table considers some of the more widely-used antennas.

Since the Sun's apparent "radio diameter" is larger for smaller antennas, the number of days of interference is also greater. Antennas of 17-meter and 10-meter diameters experience outages for about three consecutive days each season, but a 3-meter dish will suffer for about eight days in a row. The accompanying maps show typical outage tracks for the spring and fall seasons; the number alongside each track is the date and the times (in GMT) mark the middle of the outages as they sweep west to east across the country.

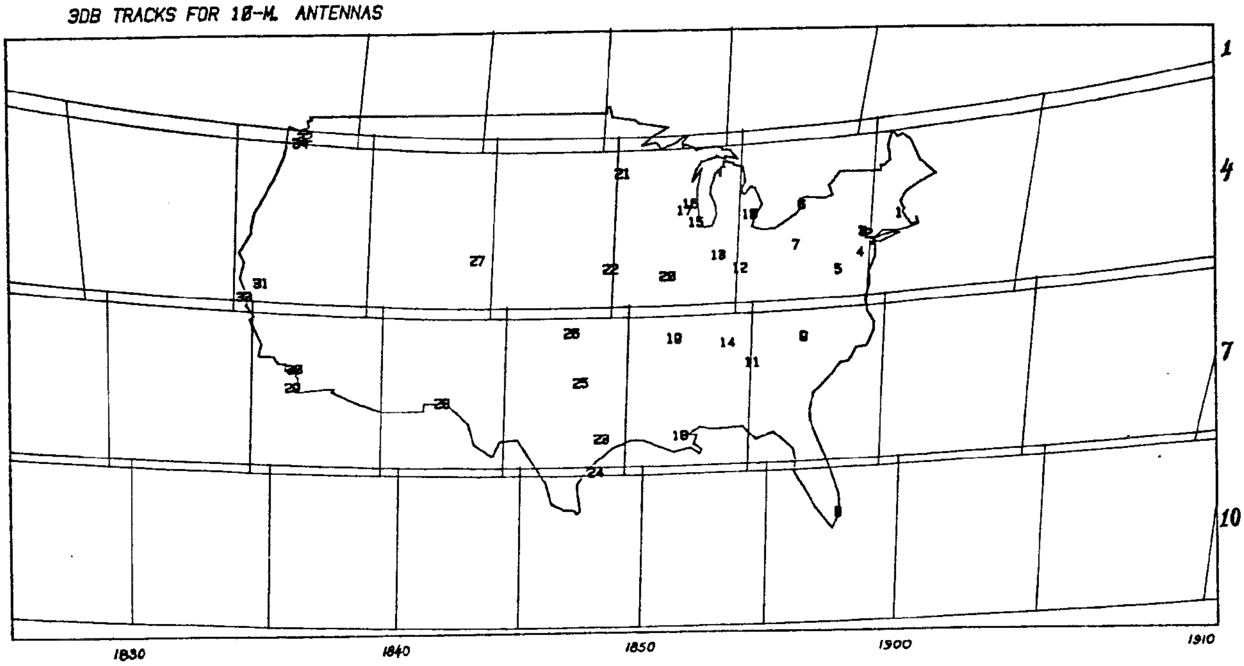
Look! Up there in the sky!

The individual users can determine where on the sky to point their dish antennas from a knowledge of the satellite's longitude and the geographical coordinates of their own locations. Their appropriate *look angles*, given as an elevation and an azimuth, can be readily computed through the use of

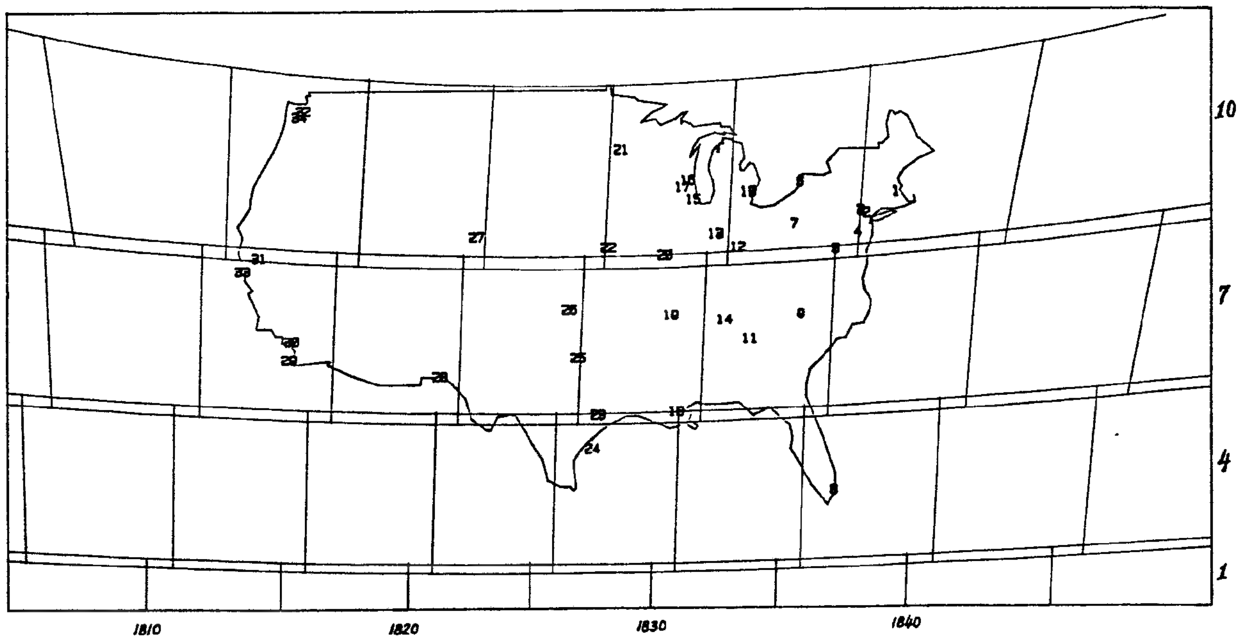
Westar-IV
Interference Tracks

MARCH 1983

3DB TRACKS FOR 10-M. ANTENNAS



OCTOBER 1983



Dates are shown along right edge of maps

Times, given as Greenwich Mean, along bottom of maps indicate midpoint of outage

analytic geometry and spherical trigonometry. We will not concern ourselves with the details here. Instead, we will consider two interesting related questions.

The first of these is the matter of just how much of the geosynchronous arc is visible from a particular station and which satellites the visible portion includes. The relevant equation is derived elsewhere and a graph of that result is depicted. We can see how this comes about. If we were at the Earth's Equator, the geosynchronous band would come straight up out of the eastern horizon, pass directly overhead, and drop straight down into the western horizon; exactly half of the circle would be visible, so all the satellites within 90° of our longitude would be visible. Because the satellites are not "infinitely" remote, as we move to higher latitudes, the geosynchronous ring appears progressively more displaced from the Celestial Equator, and so drops toward the horizon faster than the Celestial Equator does. From the continental United States, the arc is seen a few degrees south of the Celestial Equator, emerging from the horizon at points a bit south of due east and west, so slightly less than half a circle is presented to view. At our control facility in Glenwood, New Jersey (41°2 N., 74°5 W.), we can see all the spacecraft within about 85° of our longitude, from 10½° East to 159½° West, which takes in everything serving the Americas and a little of those serving Western Europe and East Asia. The geosynchronous circle ultimately vanishes below the horizon at about 81°3 Latitude; the choice of accessible satellites is seriously constrained inside the Arctic and Antarctic Circles (which has not yet created a significant problem).

The other problem of interest is that of the apparent path of a geosynchronous satellite on the sky. Most such spacecraft are found in orbits with inclinations less than 0°1 and differences between perigee and apogee of less than 10 km. The orbital inclination produces a daily variation in the latitude of the satellite. The diurnal variation in altitude brings about a variation in orbital velocity (recall Kepler's Second Law): the satellite gains and loses against the Earth's rotation, so a daily variation in longitude also occurs. These two types of motion at right angles to one another, having the same period, create an elliptical loop on the sky. The orientation of the ellipse depends on the angle between perigee and the ascending node. Because of the perturbations acting upon the orbit, the orbital inclination of the satellite gradually changes, the longitude drifts toward a stable node, and the aforementioned angle shifts, so the track is not really closed. An actual sky-track for Westar-III is shown in the first of the page of graphs; satellites with orbital inclinations less than about half a degree have essentially elliptical tracks.

A secondary effect emerges for orbital inclinations larger than half a degree. When the spacecraft crosses the Equator at a node, it is not moving parallel to the Equator, but at an angle equal to the inclination. Hence, the eastward component of its orbital motion is *less* than that needed to keep pace with the Earth's rotation, so the spacecraft appears to drift west. At an extreme of latitude, the satellite's motion is now parallel to the Equator, so the eastward component of its motion is now the full orbital velocity, but the spacecraft is over a location moving slower than the Equator, so it now appears to drift eastward. Since the satellite crosses the Equator and reaches a maximum of latitude *twice* a day, the two types of motion at right angles to each other, with a ratio of periods of 2:1, winds the sky-track into a figure-eight for orbital inclinations larger than a few degrees. For orbital inclinations larger than about five degrees, the track becomes a perfect vertical figure-eight; the track is still not actually closed, but the other effects we have spoken of are now minute by comparison.

The Operation

The maintenance of the geosynchronous "towers" entails the preservation of a *status quo*, so most of the work at the satellite control facility is routine. Each satellite is individually tracked and its telemetry is monitored with the communications antennas at Glenwood. On the basis of this information, the current orbits and attitudes of the spacecraft may be learned and the extent of necessary corrections is planned; all of this work is done through the use of interactive computer programs. The cycle of maneuvers to be conducted is generally fixed. For an HS-333, the four-week series is: attitude; inclination; attitude; drift. For an HS-376, whose attitude precesses faster, the series is: attitude; attitude; attitude adjustment, inclination, attitude; drift, attitude.

To determine the satellite's orbit, a series of measurements of its position must be made. Every hour, a signal is sent up to each satellite from its corresponding communications antenna at Glenwood and a timing of the delay in returning is made. The signal, beamed back from the spacecraft, is also picked up by a repeater station at Hughes Aircraft in Los Angeles,

The Visible Portion of the Geosynchronous Circle

For simplicity of calculation, we will assume the Earth is spherical and that the observer is at 0° longitude. We are interested in finding those longitudes on the circle for which the elevation above the horizon is zero. Let ℓ be the satellite's longitude and β_0 be the observer's latitude; the position of the satellite in rectangular coordinates with origin at Earth's center is

$$x = 6.611 \cos \ell \; ; \; y = 6.611 \sin \ell \; ; \; z = 0 ,$$

where distance is in Earth radii, and the station's location is

$$x_0 = \cos \beta_0 \; ; \; y_0 = 0 ; \; z_0 = \sin \beta_0 .$$

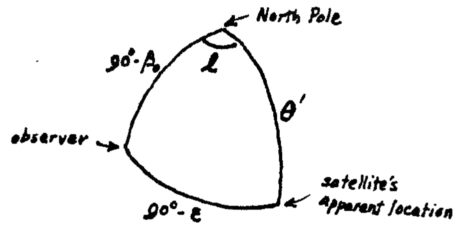
From the station, the position of the satellite is thus

$$x' = 6.611 \cos \ell - \cos \beta \; ; \; y' = 6.611 \sin \ell \; ; \; z' = -\sin \beta_0 \; ;$$

the distance of the satellite and its apparent co-declination are

$$r' = \sqrt{x'^2 + y'^2 + z'^2} \quad ; \quad \theta' = \arccos\left(\frac{z'}{r'}\right) .$$

To find the elevation, ε, seen by the observer, we need to solve this spherical triangle:



The relevant trigonometric equation is

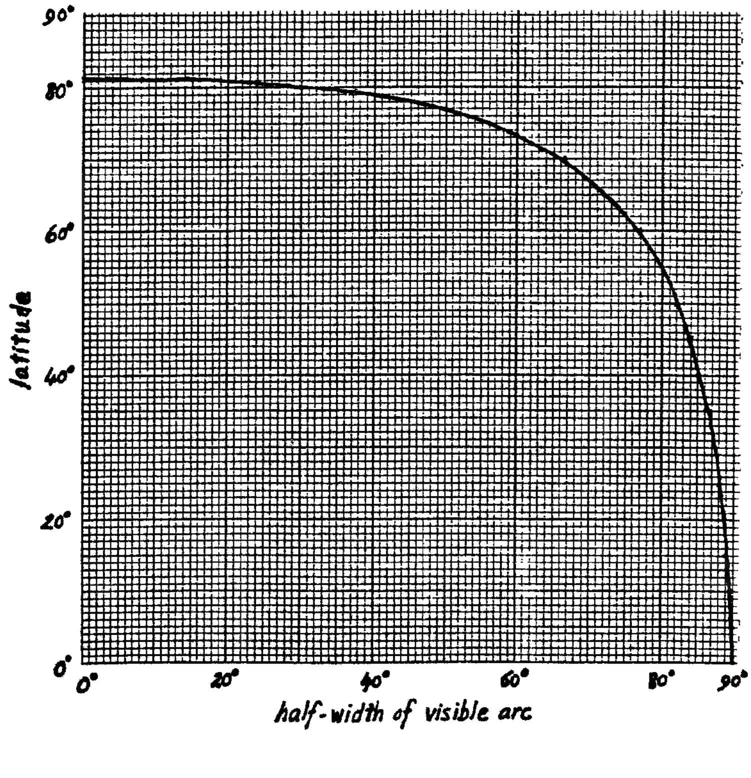
$$\cos(90° - \varepsilon) = \cos \theta' \cos(90° - \beta_0) + \sin \theta' \sin(90° - \beta) \cos \ell .$$

We are interested in the values for ℓ at which $\varepsilon = 0°$. Thus,

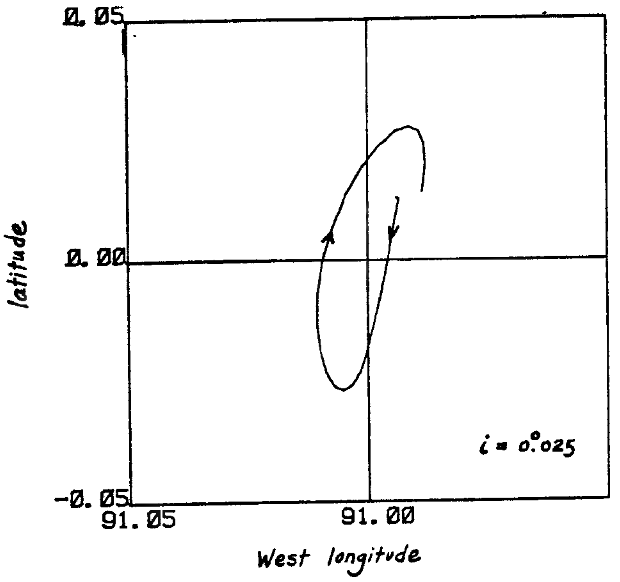
$$\cos 90° = 0 = \cos \theta' \sin \beta_0 + \sin \theta' \cos \beta_0 \cos \ell ,$$

or,

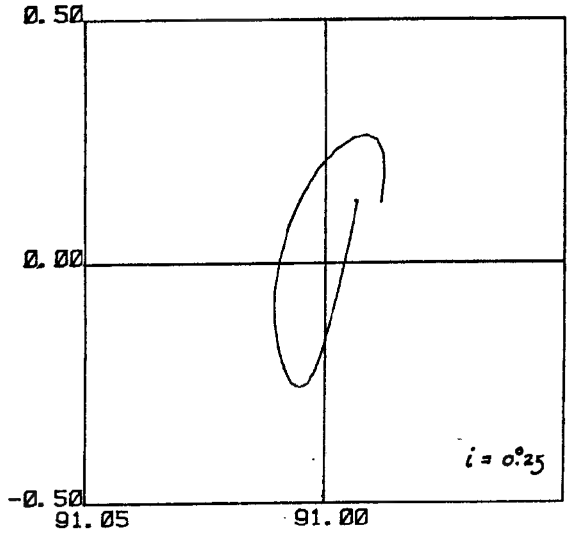
$$\cos \ell = -\frac{\tan \beta_0}{\tan \theta'} .$$

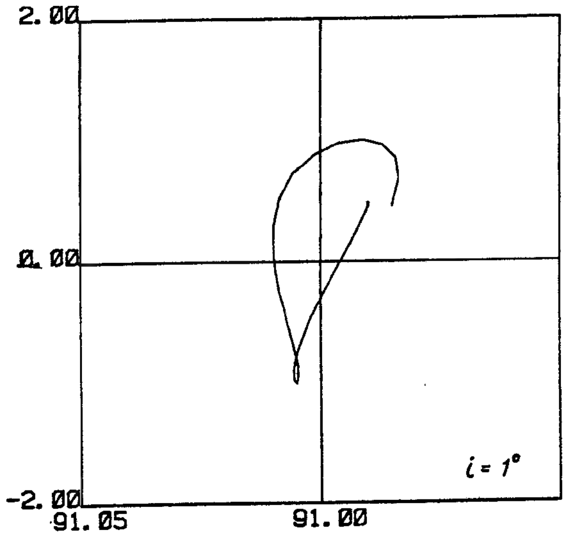


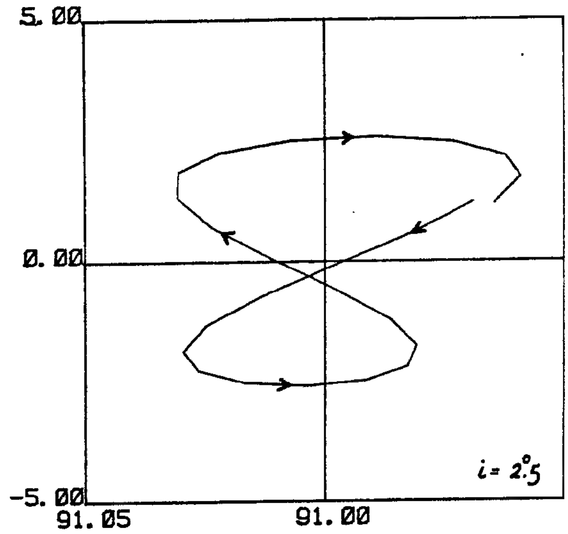
Actual sky-track for Westar - III

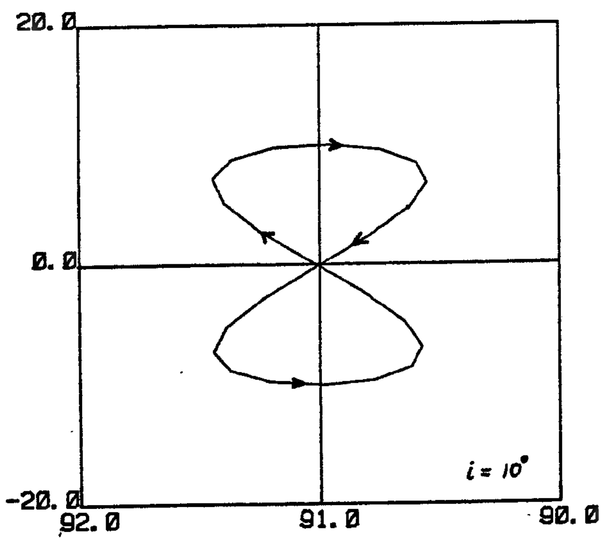


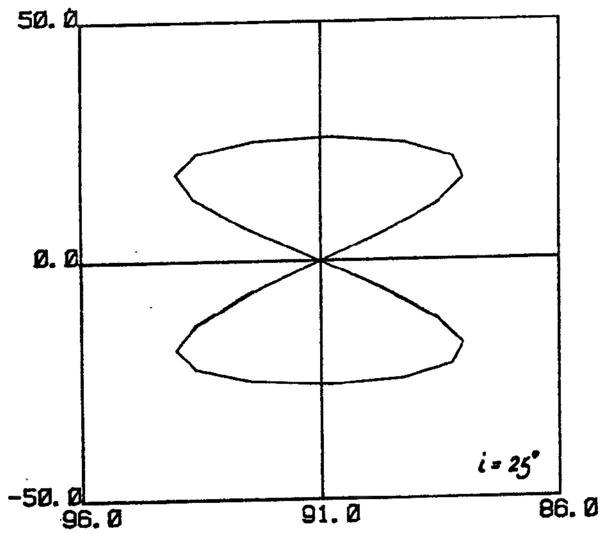
All other graphs are hypothetical











which returns the signal to Glenwood via the satellite; a measurement of this round-trip time is also taken. The distance of the satellite from both Glenwood and Los Angeles is thus known. By comparing the variation in time of these distances from the ideal position of the spacecraft, the orbit can be found through a best statistical fit of the available data. As little as twelve hours' worth of data after a maneuver can suffice to compute the orbit, although measurements are customarily collected for 72 hours.

To find its attitude, the spacecraft takes sightings on the Sun and the Earth. A photocell looking through a tilted slit measures the angle of the Sun down from the spin axis of the satellite. Two infrared sensors are swept past the Earth on each rotation of the satellite. These Earth sensors are aimed 5° above and below the horizontal; each measures the length of time that it sees the Earth's disk. The rotational period of the satellite is readily given by the interval over which these observations recur. From the known orbit, it is possible to compute where in space the spacecraft is at the time of a particular measurement. The Sun and Earth measurements and the rotational period then give an estimate of the satellite's attitude; this is again obtained by a 72-hour statistical fit.

The orbit and attitude can be extrapolated into the future by the use of models of the various forces acting on the satellite. On the scheduled day of a particular type of maneuver, this estimate is used to determine the extent of the correction needed to maintain the longitude, inclination, or attitude within permissible limits for the duration of the corresponding cycle. The time of day for the orbital correction is also found, if appropriate.

The satellites are not intelligent: they do not automatically know in which direction the Earth lies or in what direction a given thruster must be fired. In order to keep the antenna reflector on the satellite facing toward the Earth, it is mounted on a counter-rotating platform atop the spinning body of the satellite. A beacon from the ground is sent to each satellite to provide an alignment reference for the reflector; this signal then guides the platform's servomechanism to provide the proper rate of counter-rotation. The beacon for Westar-II is sent from a station at Cedar Hill, Texas; for Westar-III, from Estill Fork, Alabama; and from Glenwood for the HS-376s.

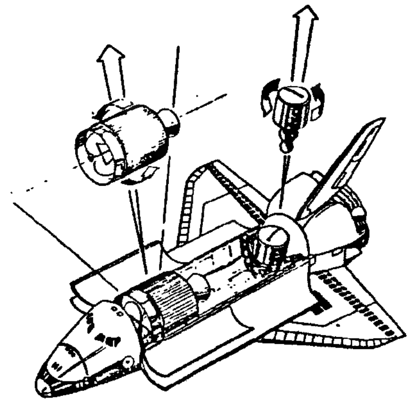
Commands to the spacecraft are also sent from these beacon sites. When an attitude or drift maneuver is to be performed, the requisite thruster must be aimed at a particular direction in space. (Inclination maneuvers simply involve firing both axial thrusters continuously for a specific interval.) At the time of the maneuver, that direction makes a certain angle with respect to the direction of the Sun. The computer at the satellite control facility constructs a string of commands to fire the thruster once per satellite rotation. The firings must be set up to wait from the time the Sun sensor sees the Sun sweep past until the time when the desired thruster is facing the right way. The timing must also take into account the delays incurred in sending the commands from the computer through the wiring and microwave links to the corresponding beacon facility and then out into space to the satellite. The computer sends the string "fire ... fire ... fire ..." for the necessary number of thruster pulses and then clears the command.

Not the end

The number and variety of geosynchronous communications satellites promises to increase with the passage of time. In addition to the over 150 objects already on the magic circle, there may be another two hundred by the early 21st Century. The demand for transponders will continue to grow with the expansion of cable and direct-broadcast television services, video teleconferencing, vocal telephone connections, computer data links, and other needs of contact between different points on Earth.

There has been a trend over the last twenty years, since the Hughes Syncoms of 1963, toward progressively larger geosynchronous communications satellites. The largest satellites which Hughes Aircraft is designing for this intent are the Intelsat VI and HS-393 series. These spacecraft mass around 1200 kg. (2650 lb.) and have diameters of about 3.7 m. (12 ft.); the Intelsat VIs, when their antennas are fully deployed, will measure 12 m. (39 ft.) from end to end. These satellites are so large that they cannot be stood up in a space shuttle orbiter's cargo bay, as can the HS-376s. Instead, they are carried into orbit "lying down" in the bay; when released, they are ejected sideways and are spun up as they depart, in what has been termed the "Frisbee" technique. They are massive enough to require a Minuteman-III booster engine to place them into transfer orbit.

A "folded" HS-376 leaves the rear of the cargo bay by the conventional spring ejection method. The "folded" HS-393 is released using the "Frisbee" or roll-out technique.

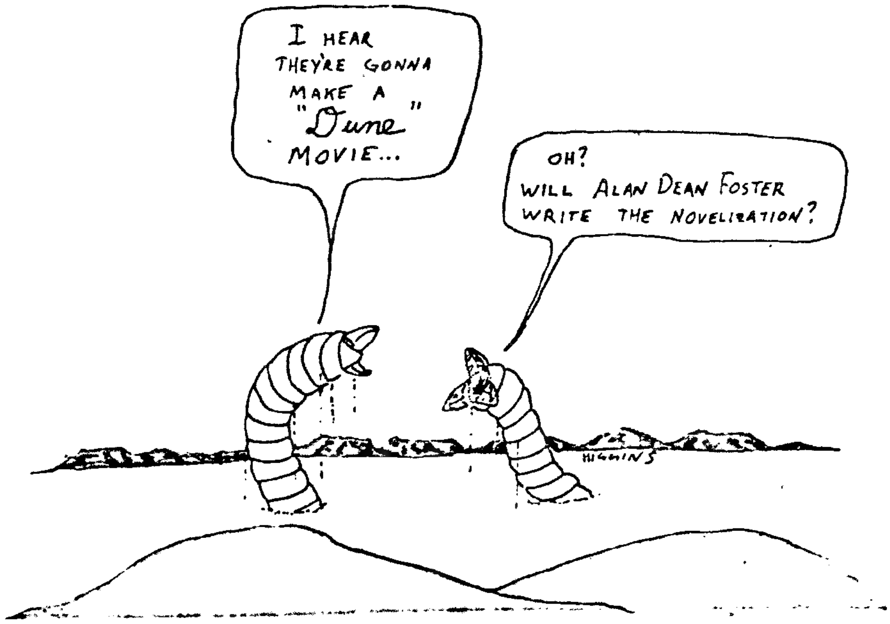


These are the largest such satellites which Hughes has said it will ever build. As the geosynchronous ring grows more crowded, it will become harder to place satellites operating in a particular frequency band in locations where they will not interfere with one another. Still, the information-carrying capacity of the circle must be increased. One approach which Hughes is examining is the use of satellite "clusters": six satellites are placed into orbits so that they all fit within the same operating "box" at one longitude and will follow each other along the same elliptical sky-track, separated in phase by 60°. This could be done by using six similar orbits with the ascending nodes 60° apart from one another and with the same angle between ascending node and perigee for all of them. All would then lie within a single communications antenna beam and would act as a single satellite with six times as many transponders as a regular one. (The station-keeping task would be *at least* six times as formidable.)

Others are considering the construction of still larger spacecraft and the eventual creation of whole communication stations in geostationary orbit. By the early 1990's, the Ariane-5 launch vehicle and the Transfer Orbit System, which will be used from a Shuttle orbiter, will be able to place spacecraft in the three-to-five-tonne mass range at locations on the geosynchronous band. With the appearance of second-generation re-useable launch vehicles around the turn of the century, which could reduce launch costs to $150 per pound, round-trip service to geosynchronous altitude could become practical. Repair of existing satellites or the construction of large operational stations might be possible early in the next century.

There is a developing trend toward greater automation both aboard the satellites and in operations on the ground. As a satellite ages and on-board fuel is consumed, the internal mass distribution changes, which can gradually cause the spacecraft to wobble as it spins. Hughes has incorporated circuitry into the HS-376s to command occasional thruster firings automatically, in order to change the satellite's angular momentum and thus control the "wobble." As microprocessors become more sophisticated, satellites may be made more "intelligent." With companies enlarging their fleets of communications satellites, the endeavor of station-keeping will become greater and more complex. Telesat Canada, which will have nine HS-376s in service by 1986, has already automated the work of attitude maintenance. The system computer collects attitude data, continuously updates the attitude estimate, notes when the satellite is approaching the operating limit, and prepares a description of the necessary maneuver. Human intervention is only required to verify the accuracy of the generated maneuver and to transmit the command to the spacecraft. The Canadians plan to introduce automated orbital control into their system imminently. With the eventual completion of the Tracking and Data Relay Satellite System in 1985, control stations may be relieved of the task of tracking their own satellites; it would be possible to obtain positional data or a current orbital description from the TDRS center at White Sands, New Mexico.

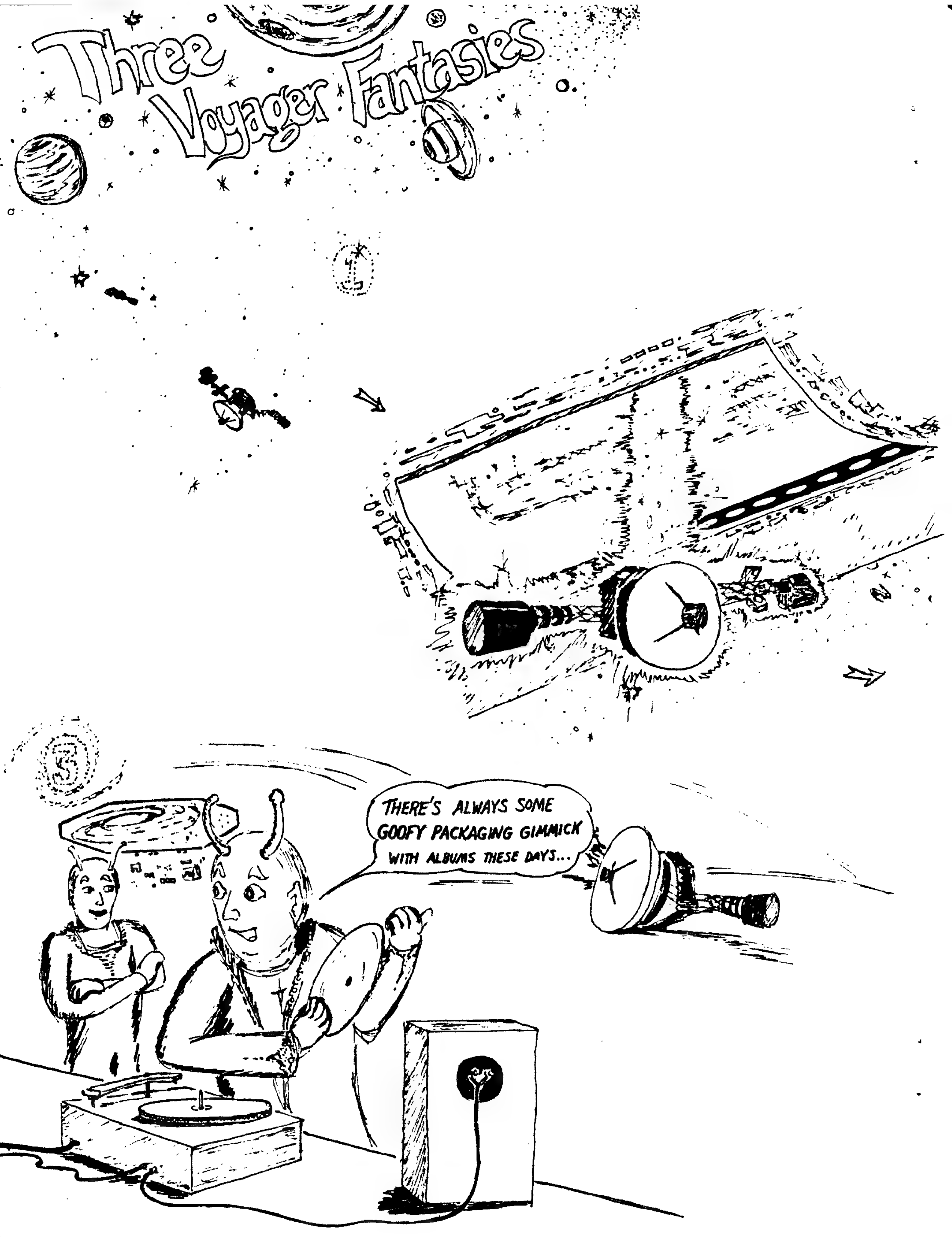
It is planned that the time will come when virtually all of the control of geosynchronous communications satellites will be conducted from orbit, while the ground stations reserve the sole task of directing the flow of information. The great towers, which will help bind the world together, will be cared for by men and machines working together in space.


I HEAR THEY'RE GONNA MAKE A "Dune" MOVIE...
OH? WILL ALAN DEAN FOSTER WRITE THE NOVELIZATION?
HIGGINS

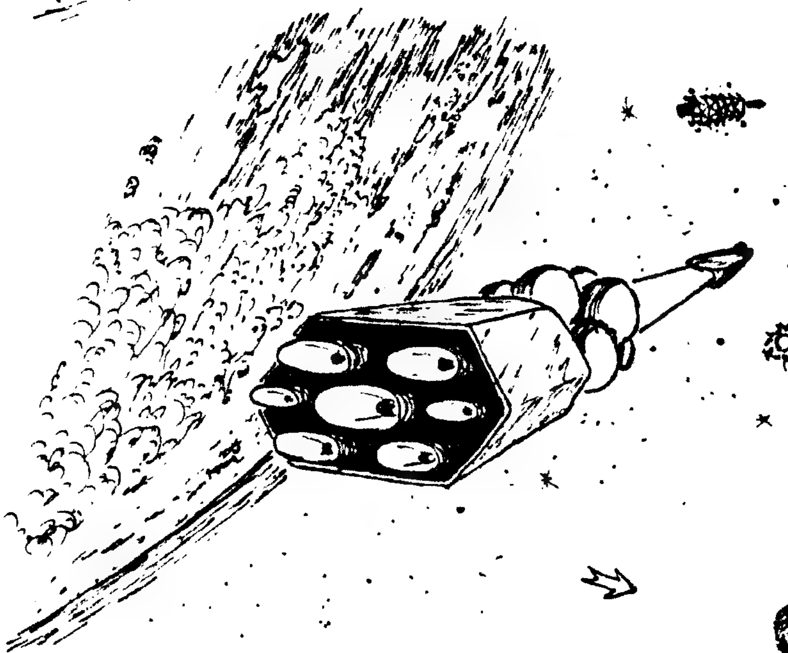

Jet Propulsion La
Image Processing
SAY, IT'S ONLY A FRACTAL MOON HANGIN' OVER A SOFTWARE SEA BUT IT WOULDN'T BE MAKE-BELIEVE IF I HAD MY CRAY THREE...

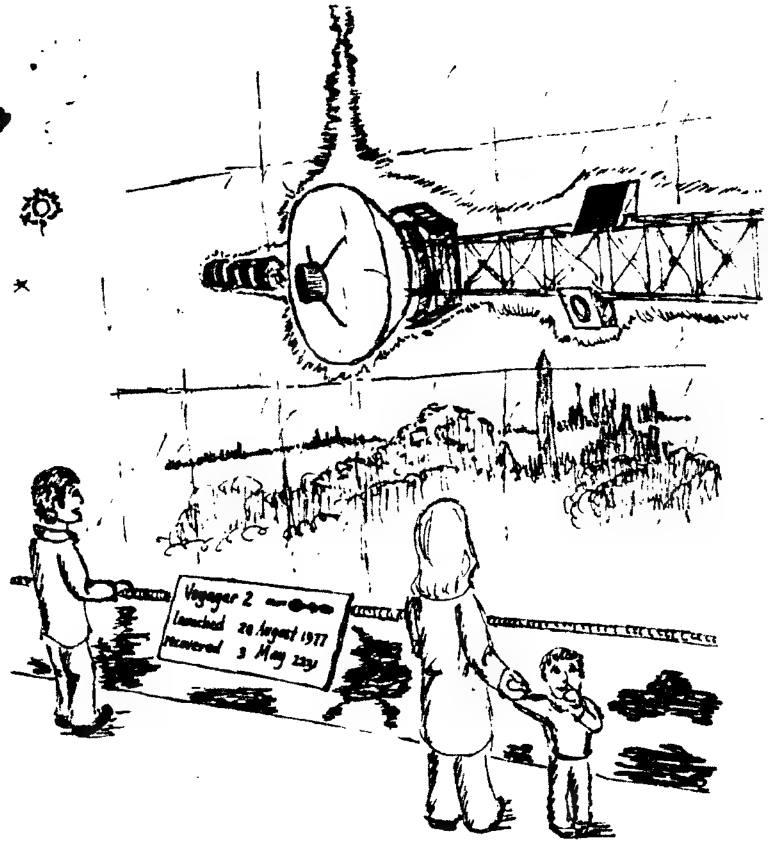

?
WATCH OUT FOR FALLING STEINWAYS
HIGGINS

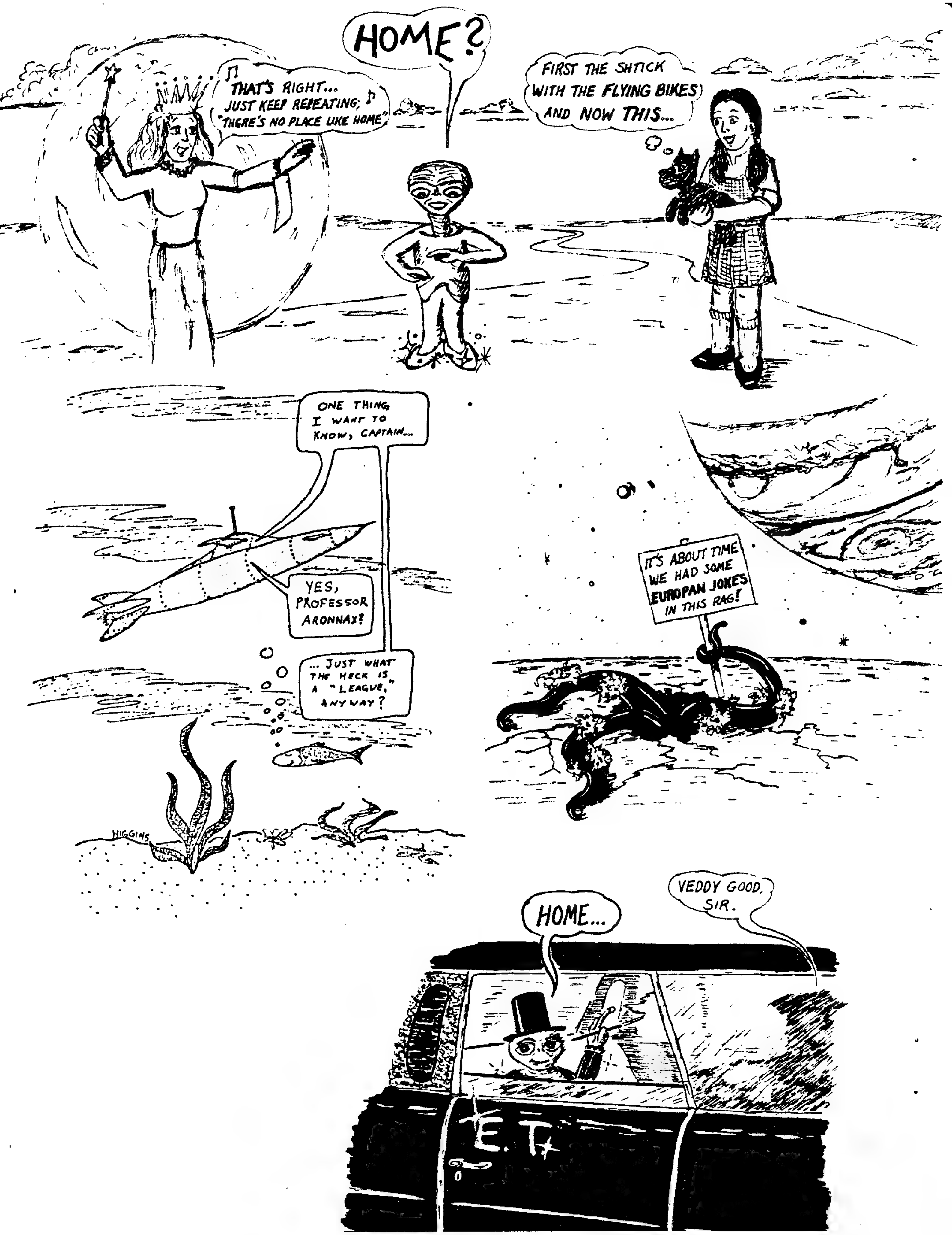

HOME?
WRONG-O, CHUM! THIS HERE'S DOWN. HOME'S MORE OVER TOWARD SAGITTARIUS...


Three Voyager Fantasies
1
3
THERE'S ALWAYS SOME GOOFY PACKAGING GIMMICK WITH ALBUMS THESE DAYS...


CORNELL UNIVERSITY
Department of
Astronomy and
Space Sciences
GALACTIC POSTAL SERVICE
Returned for Postage
Cannot be Delivered as Addressed
Use Mr. Zip




Voyager 2
launched 20 August 1977
3 May


THAT'S RIGHT... JUST KEEP REPEATING, "THERE'S NO PLACE LIKE HOME"
HOME?
FIRST THE SHTICK WITH THE FLYING BIKES AND NOW THIS...
ONE THING I WANT TO KNOW, CAPTAIN...
YES, PROFESSOR ARONNAX?
... JUST WHAT THE HECK IS A "LEAGUE," ANYWAY?
HIGGINS
IT'S ABOUT TIME WE HAD SOME EUROPAN JOKES IN THIS RAG!
HOME...
VEDDY GOOD, SIR.
E.T.

Nertz & Boltz

Bill Higgins
looks at books on space

The Space Shuttle Operator's Manual
Kerry Mark Joels and Gregory P. Kennedy
Designed by David Larkin
1982; 145 pages
Ballantine Books
$9.95 paperback

Well, the title is slightly misleading. We all know that the real manuals for the Space Shuttle make a stack higher than a fully deployed Westar. The authors, however, have done us the service of boiling down that stack into a single, well-illustrated volume.

All the essentials of the Shuttle's operation are here. The text covers general design, subsystems, and procedures in simple language. It is well complemented by photos and two-color diagrams on nearly every page. They illustrate such points as the donning of spacesuits, details of some payloads, layout of instrument panels, and mission profiles. The flight deck consoles are pictured in three foldout charts.

Detailed timelines for launch and reentry are given, including radio "callouts" and instructions on which switch to throw and which dial to watch for each procedure. The book will also tell you how to fix meals, use the airlock, the toilet, the manipulator arm, and the galley.

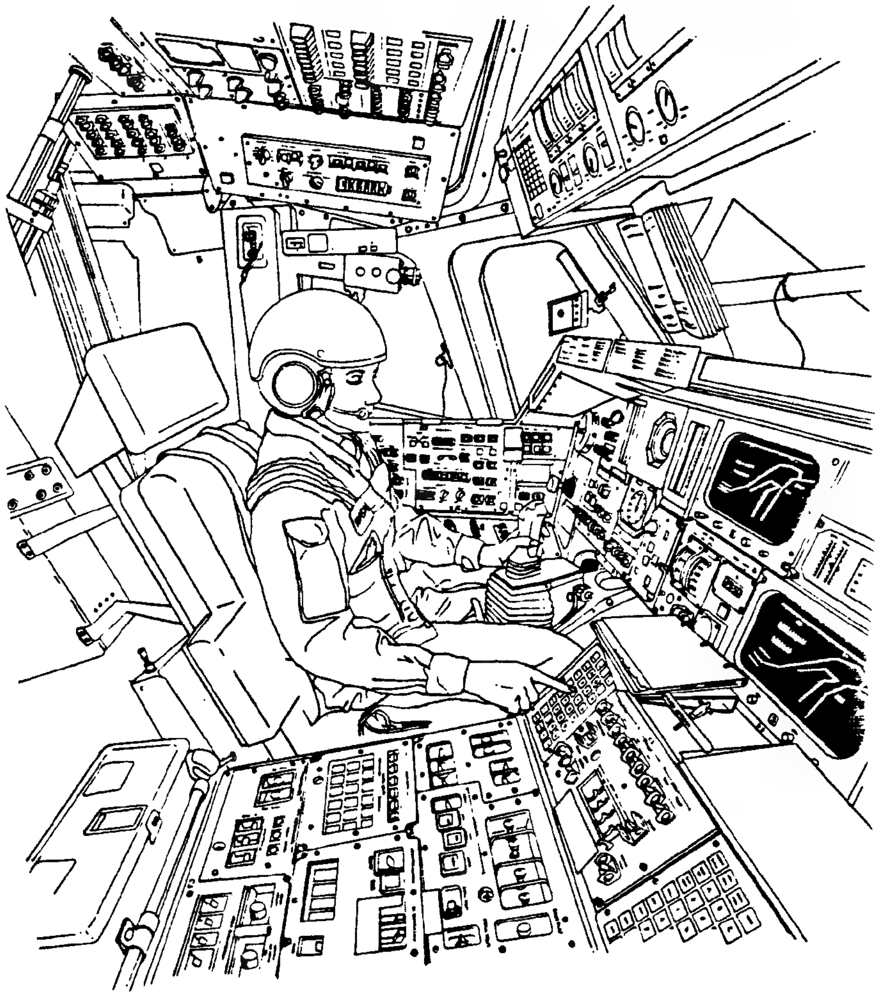
To keep their Manual at a moderate length, Joels, Kennedy, and Larkin had to eliminate many contingencies and a lot of detail that was either highly technical or specific to a particular mission. Only a brief space is given to emergencies. If everything goes normally, though, the book will be a good guide to events.

Unfortunately, the authors chose to address the reader as though he were actually boarding the Space Shuttle, which produces some unintended humor ("READ BEFORE LEAVING ORBIT"). Let's face it, only a few of the readers will ever set foot in a Shuttle-- and those that do will be given copies of the aforementioned real manuals, right?

The jacket blurbs are even worse. "YOU ARE THE PILOT OF THE SPACE SHUTTLE!... Soar into the sky consulting the authentic gatefold reproduction of the Shuttle's instrument panel." Hope you can read it under 3G acceleration, with the ship vibrating around you.

The Manual is certainly good enough to stand on its own without such a silly approach. It will be invaluable to the Shuttle-watcher who wishes a thorough amateur-level understanding of the way the spacecraft works. I must admit, though, that if a twelve-year-old space cadet studies it, and does manage to stow away, he'll feel right at home...

LAUNCH AND ASCENT 1.14



FLIGHT DECK, COMMANDER'S LAUNCH POSITION

New Earths
Restructuring Earth and other planets
James Edward Oberg
Foreword by Jack Williamson
1981
Stackpole Books
Cameron and Keller Streets
PO Box 1831
Harrisburg, PA 17105
$16.95

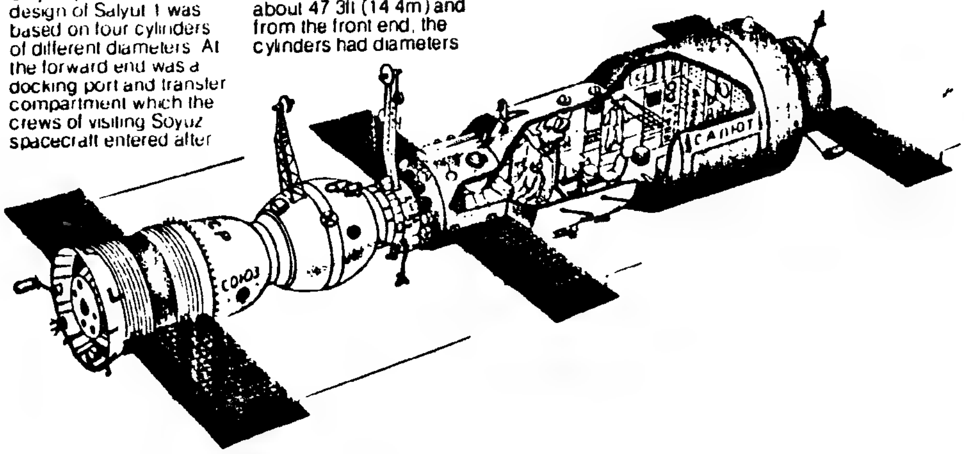
Beyond Earth there lie numerous planets, even more numerous moons, and innumerable asteroids, comets, meteor swarms, and similar debris. Some of these bodies consist of rocky and metallic material, while others are mostly formed of volatile gases and ices. And, of course, there are various gradations of mixtures. All are lit and heated by the nuclear fires of the Sun; some have their own internal heat sources as well.

Through terraforming, mankind will rearrange these physical objects, altering their movements and radiation balances, breaking them up or pushing them together, in order to create Earth-like worlds. Even here the definition of "Earth-like" is still unresolvable; the best we can say is that these rebuilt worlds will be capable of supporting Earth-derived life, including people, without significant restrictions.

New Earths is the first book devoted entirely to terraforming, the art of making other planets habitable. We now know just enough to move it from the handwaving stage to back-of-the-envelope calculations.

A good review of the way the biosphere works and the way it evolved is followed by a look at the ways we could change our planet-- including the mistakes we might make (and have made). Mars, as the most promising target for terraforming, gets a lot of attention from Oberg. Venus, the Moon, Mercury, and the satellites of the gas giants are more difficult. Perhaps they can be tackled as planetary engineers gain in experience and capability.

Salyut 1
To test the ability of men to work in space for long periods Russia developed a series of Salyut space stations The design of Salyut 1 was based on four cylinders of different diameters At the forward end was a docking port and transfer compartment which the crews of visiting Soyuz spacecraft entered after they had docked Two pairs of wing like solar panels opened fore and aft once the vehicle had arrived in orbit The station had an overall length of about 47 3ft (14 4m) and from the front end, the cylinders had diameters of about 6 56ft (2m); 9 5ft (2 9m), 13 6ft (4 15m) and 7 2ft (2 2m) The last cylinder contained the manoeuvre engine This view shows Soyuz 11 docked with the station The large conical telescope housing has been removed from the cut away of the interior



Many controlling factors in a biosphere depend on materials or energy flows which are remarkably small; modulation of such environmental fulcrums by natural or artificial levers (intentionally or accidentally) can produce effects out of all proportion to the material and energy expended. To coin a metaphor, it is a type of biospherical ju-jitsu, where tiny slaps and shoves can use the momentum of the whole planet to completely change its biological course, without directly confronting the massive energy flows of planetary climate.

On Earth, such fulcrums may be vulnerable to artificial perturbation to the extent that our planet could be rendered uninhabitable by the manipulation of a proportionately tiny amount of energy or matter. Conversely, on other worlds, a similarly gentle and subtle tickling of such fulcrums may make their environments more benign.

The physical climate and chemical makeup of a planet would probably be altered using a combination of techniques. Orbiting mirrors or shades can control the amount of sunlight available. Dropping icy asteroids can add volatiles to an atmosphere; collisions and near-misses can transfer angular momentum to the planet. Tailored microorganisms may slowly change the composition of the biosphere. The synthesis of an entire ecology which maintains a stable environment is a harder, more vaguely defined problem.

Oberg seems convinced that terraforming will indeed be attemped someday. He does, however, discuss some objections to terraforming and the ethical issues raised. As he notes, we don't even know enough yet to know whether it's worth doing...

New Earths is for the general reader; more technical discussion will have to wait until Oberg finishes editing The Terraforming Papers, a forthcoming collection of research and commentary.

The Illustrated Encyclopedia of Space Technology
edited by Philip de Ste. Croix
Consultant and Chief Author: Kenneth Gatland
Foreword by Arthur C. Clarke
1981; 289 pages
Harmony Books
Crown Publishers, Inc.
One Park Avenue
New York, N.Y. 10016
$24.95

Let me be brief. If you could own only one book on astronautics, this would have to be it.

No space in this coffee-table volume is allowed to go to waste. The index is in teeny-tiny print, and even the endpapers are crammed with statistics on launch vehicles. Each of the twenty-one chapters covers a historical, contemporary, or speculative aspect of space flight. There must be hundreds of color illustrations by half a dozen artists; almost every significant piece of hardware, whether it flew or not, is portrayed. Some pains were apparently taken to obtain seldom-seen photographs, too, rather than reprint the chestnuts one more time.

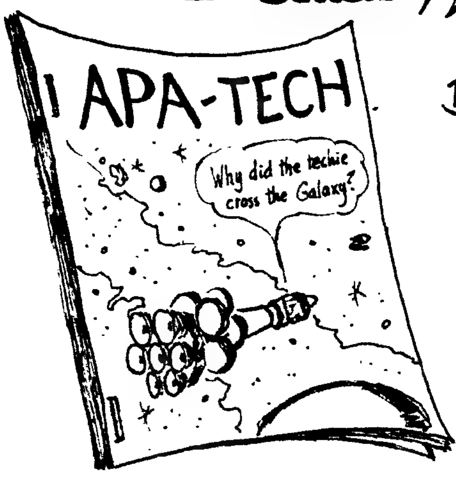
Some of the book's unique goodies: A fold-out scale illustration of every satellite launcher of the world. Maps, laboriously compiled by Charles Vick from Landsat photos, of Soviet and Chinese launch complexes, not to mention those of the U.S., Japan, India, ESA, and Italy. Detailed cutaways of the Stanford Torus space colony, the Daedalus interstellar probe, a space manufacturing facility. A thick chronology of astronautics. Another foldout with large drawings of Skylab and Salyut.

Gatland has gathered his buddies from American and British members of the British Interplanetary Society, plus one Russian and one Belgian. They are knowledgable professionals, and if they toot the BIS's horn a bit, other histories tend to underrate the group. After all, their studies of lunar landers, satellite vehicles, and interstellar flight have been way ahead of their time. The BIS serves as a valuable forum, not only for advanced (sometimes crazy) ideas on astronautics, but for important work with contemporary technology. It's a vital exchange of information for amateur analysts of Soviet space activities.

The Illustrated Encyclopedia of Space Technology-- while not a Society publication-- represents one of the BIS's finest efforts yet. It is a splendid, colorful summary of where we've been and where we hope to go in space.

LOOKING for a Technological fix?

Join THE OTHER magazine!!



BY AND FOR Gers

STARSHIPS!

SUBMERSIBLES!

AI!

~~SAPPY~~ ~~NATTER~~ SNAPPY PATTER!

MORE!!

COMING IN DECEMBER

SPECIAL "ROBOTS" ISSUE

WRITE FOR DETAILS TO:
RENEE SIEBER, EDITOR, 525 W. WALNUT, KALAMAZOO, MI 49007

THE Urban Eyeball

Naked-eye Astronomy for City Folk

Part I: the Autumn Sky

People who live in modern industrialized nations typically have little familiarity with the features of the night sky. The tremendous intensity of illumination in urban areas creates an artificial skyglow which outshines all but the brightest natural sources. Of the roughly 8000 stars which are detectable by the human eye in the skies of Earth during the year, perhaps only a couple dozen are bright enough to be seen from within a city. The situation is somewhat better in suburban regions, but, even so, most of the ancient constellations remain lost in the orange haze.

I have long felt it would be worthwhile to produce a set of charts for the diminshed urban sky, in order that more people may come to know at least the bright stars and then in turn learn to distinguish the planets. I've sometimes found a knowledge of stellar locations useful in regaining a lost sense of direction while travelling. By learning the bright stars first, I think it also becomes easier to learn where more of the stars are and to pick out the constellations when one has an opportunity to visit a locale which is truly dark at night.

The maps show the visible hemisphere of sky seen from the continental United States: a large map is prepared for an observer at 40° North latitude and smaller ones are given for observers at 50° and 30° North. The projection used is one which preserves area, so the relative sizes of the constellations pretty nearly resemble what one would actually see. There will be four sets of maps, one for each season (hence, this is the first of four quarterly articles). The time when the sky appears as shown in each set is indicated for the first of each month; because the Sun makes a complete circle among the stars in one year, the time when the sky attains a specific arrangement occurs about two hours earlier each month.

The maps present the view one would have in lying on one's back with toes pointing due south; the circle represents the horizon and the center is the zenith, the point directly overhead. Orienting oneself can be easy for a city dweller. Many people already know which direction is north where they live and many cities obligingly use street grids aligned (at least pretty closely) with the cardinal points. As another hint, the place on the horizon where one sees sunset occur also indicates roughly where "west" is. Alternatively, one could use the maps themselves as a guide and, in comparing them against the night sky, locate the compass points for future reference.

The sizes of the star symbols are proportional to the brightness of the actual stars in the sky. Stellar brightnesses are ranked according to a *magnitude* scale. The original system was arranged by Hipparchus some 2200 years ago and modified by Ptolemy two centuries later. The very brightest stars were called "first magnitude," those slightly dimmer were designated "second magnitude," and so on down to "sixth magnitude," those stars just discernible to the unaided eye in a very dark, clear sky. By the middle of the Nineteenth Century, it became possible to measure the *amount* of light reaching us from individual stars. Norman Pogson of England established a quantitative basis for Hipparchus' system in 1850. He found that the average first-magnitude star was about 100 times brighter than the average sixth-magnitude star. Hence, five steps in magnitude represent a factor of 100 in the amount of light reaching Earth; a single step is a factor of $\sqrt[5]{100}$ or about 2.5 in brightness (for you engineers, that's 4 dBW). When this relationship was determined, it was found that there are stars *more* than 100 times as bright as sixth-magnitude, so the magnitude scale had to be extended upward beyond first-magnitude. Vega, for instance, is magnitude 0.0 and the brightest of stars in Earth's skies, Sirius, is magnitude -1.5; by comparison, the Sun is magnitude -26.7. Of course, with the invention of telescopes, stars dimmer than sixth-magnitude are observed: the faintest objects which we can presently detect are of about magnitude 23.

Because the urban night sky is so bright, the faintest stars which may be seen on a good night are of about magnitude 2.5, so the maps will show all the stars brighter than magnitude 2.75. Those constellations which have enough bright stars to be recognizable *as* constellations have been drawn in and labelled. The names of all the stars of at least magnitude 1.5 are given. Other objects of interest, which are not necessarily visible, have also been marked. The planets are not shown, since their positions can change greatly in three months.

This first set of seasonal maps shows the autumn sky as it appears around midnight in October and in the early evening in December.

* * *

The western portion of the autumn sky is dominated by three bright stars arranged nearly into a right triangle. The constellation *Cygnus* extends into this triangle from one of the vertices. All the ancient Western civilizations saw this as some sort of bird; the Greeks referred to it as a swan, a designation already quite old when it reached them. Modern observers also see this as "the Northern Cross."

The Swan is perceived to be flying to the west, its long neck extended. The star at its tail (or at the head of the Cross) is *Deneb*, which simply means "tail" and derives from the Arabic *Al Dhanab al Dajajah*, "the Tail of the Hen" in their view of the constellation. Deneb is one of the most powerful stars known. It is a good example of the disproportionateness between the mass of a star and its luminosity: Deneb is estimated to be 25 times the mass of the Sun, but emits about 60,000 times as much power. Deneb would appear as bright as our Sun to an observer six times as far from the former as Pluto is from the Sun. One would imagine that such a tremendous release of energy would exhaust the available fuel for stellar fusion rather rapidly. Indeed, present models of stellar evolution (the theory of how stars are formed, age, and expire) indicate that Deneb can only maintain its existing stable state for an interval of about 15 to 20 million years, while the Sun can sustain its present stability for about 9 to 10 *billion* years (we are now around the midpoint). Deneb must therefore have been recently created in cosmic history. This star is perhaps 60 times the size of the Sun and has a surface temperature of about 9700 K (17,000° F), making Deneb appear bluish-white to the human eye. The spectrum of the star exhibits somewhat regular variation in the Doppler shift of its lines, with a period of 11.7 days, and a small variability in brightness of 0.05 magnitudes. This suggests that the atmosphere of Deneb may be pulsating or experiencing large-scale turbulence. Deneb is about 1600 light-years away, making it one of the most distant of our bright stars.

Vega, the fifth brightest star in our night skies, lies in the constellation Lyra, which represents the lyre, the musical instrument invented by Hermes, passed in turn to Apollo and, ultimately, to Orpheus. The star's name comes from the Arabic *Al Nasr al Waki'*, "the Swooping Eagle," sometimes shown bearing the lyre in its beak. Vega lies near the circle of precession followed by the Earth's spin axis: it served as our Pole Star some 14,000 years ago (coming closest around 12,400 BC) and will act in this role again, the North Celestial Pole passing within 4½° of it about 13,400 AD. It is something of a stellar neighbor, lying only 27 light-years away. Vega is about three times the mass and diameter of the Sun and is 58 times as luminous; its surface temperature is about 9200 K (16,100° F), so its color is white. It was the first star ever to be photographed: astronomers at Harvard Observatory made a daguerreotype on July 17, 1850.

Altair, of the constellation Aquila the Eagle, obtains its name from *Al Nasr al Tair*, the "Flying Eagle." It is a very close neighbor, being just 16 light-years distant. It is about 1½ times as big as the Sun and nine times as luminous; Altair is a bit cooler than Vega and also looks white. It is one of the most rapidly rotating stars known: it turns once around in just 6½ hours (by comparison, the Sun's Equator completes a rotation every 25½ *days*); it is believed this makes Altair extremely oblate, with its equatorial diameter nearly twice the distance from pole to pole.

The center of the autumn sky is filled by a set of constellations connected by a single myth, which contemporary Americans please to call the "Clash of the Titans" story. This is the tale (too long to repeat here) relating Cepheus and Cassiopeia, the king and queen of Ethiopia; their daughter Andromeda; the hero Perseus; the dread Gorgon, Medusa; and the sea monster, Cetus. Cepheus is too faint to interest us here, but we shall look at these other asterisms.

Cassiopeia is seen as a letter "W" or "M" in the sky as it circles the North Celestial Pole. This was actually seen as the throne in which Cassiopeia was eternally condemned to sit, spending most of her time suspended upside-down.

Andromeda and *Pegasus* are linked together at the northeast corner of the large quadrangle of stars known as "the Great Square of Pegasus." The story of Andromeda and the corresponding constellation is probably traceable to the Babylonian *Epic of Creation* of about 3000 years ago. Pegasus, the winged horse, sprang into being, by Neptune's command, from the blood of Medusa as it dropped into the sea from the head severed by Perseus.

An object of interest in this region is the Andromeda Galaxy, also known as *M31* and NGC 224. The first of these technical designations arises from its appearance in the catalogue of Charles Messier, the Eighteenth Century French astronomer and comet-hunter, who compiled a list of objects which were *not* comets and were to be avoided in future searches. The latter term refers to the Galaxy's entry in the New General Catalogue (1888) of John Dreyer; this book was a collection of non-stellar objects and dates from a time when "spiral nebulae" were believed to be part of our Milky Way. This particular object is the nearest and brightest spiral galaxy to us. In a dark sky, it is visible as a faint smear, which is actually but the central core of the whole galaxy which spans over 3°, more than six times the breadth of the full Moon. Its galactic nature (and, in fact, the existence of galaxies as distinct entities in a *very* large Universe) was only recognized in the 1920s. The Andromeda Galaxy is now believed to lie about 2.2 million light-years away. It is estimated to contain about 500 billion stars and is about 160,000 light-years across, about half as big again as the Milky Way. As our Galaxy is accompanied by the Magellanic Clouds and "Snickers," so M31 is joined by four galactic companions (NGC 205, M32, NGC 185, and NGC 147), all dwarf elliptical galaxies (small "football-shaped" aggregations) containing only tens of millions of stars. The Milky Way, its associates, and the Andromeda Galaxy and its family are the dominant members of a grouping of twenty-odd galaxies which we speak of as the Local Group.

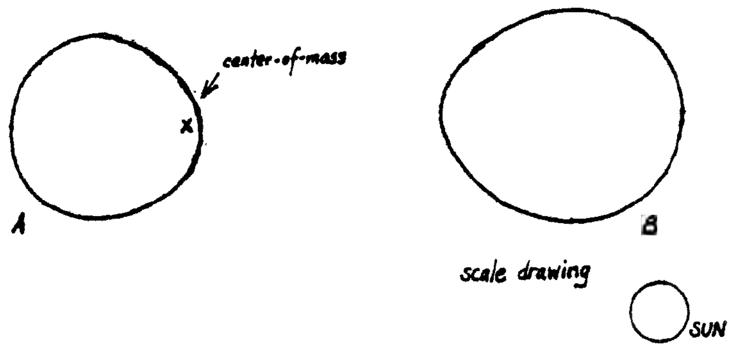
The sea monster, *Cetus*, was sent to devour Andromeda; it was defeated by Perseus, who turned it to stone with the gaze from the dead Medusa's head. This constellation is also seen as a whale. It is one of the largest constellations in the sky, although rather undistinguished in brightness.

An interesting star in Cetus is *Mira*, from *Stella Mira*, "the Wonderful Star." It was the first long-period variable star to be discovered, since it is the brightest, and so the best-known, of such objects. Its brightness varies from 9th to 3rd magnitude typically, but it has been seen to reach second and even first magnitude (in 1779). The period of its variations averages 331 days, but both the period and range of brightness are slightly irregular; every maximum of brightness has been observed since 1638. Mira is about 220 light-years removed from us; its mass is about twice that of the Sun and its diameter has been measured by interferometry to be 400 times the Sun's, making it bigger than the orbit of Mars. Its luminosity changes from about 1 to 250 times the Sun's in the range of visible light; across the whole spectrum of radiation, the variance is more like a factor of 2.5. The surface temperature ranges from 1900 K (3000° F) at minimum light to 2500 K (4000° F) at maximum. It is thought likely that minute grains of carbon and some metals actually condense out of Mira's atmosphere at minimum; molecules such as water vapor have also been detected. What we see in Mira is an aged star which has consumed all the hydrogen at its center and has entered a state of red supergianthood for the last ten percent of its life. It is passing through a phase of mild structural instability which causes the star to pulsate physically; this occurs only briefly during this time on the way to death. Mira is not believed to be massive enough to die as a brilliant supernova; instead, perhaps some few hundred million years from now, the outer layers of the star will be blown off into space (by a process not well understood), leaving the inert though very hot core exposed to space as a white dwarf. Mira orbits with a small, hot, peculiar star which may have greater mass. Binary stars can greatly alter the development of one another in old age: Mira's companion may be a dead white dwarf scooping up hydrogen from the supergiant and "burning" it on its surface, making it hotter than it "should" be.

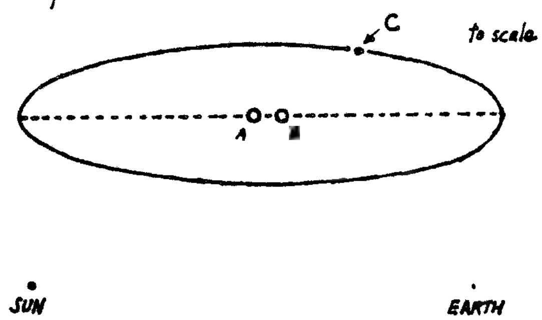
The hero of the Autumn Sky Myth is *Perseus*, the slayer of Medusa and Cetus and rescuer of Andromeda. He was also taken to be the legendary progenitor of the Persian people.

A different sort of variable star is *Algol*, from *Rās al Ghūl*, "the Demon's Head"; Algol was perceived to be the flickering red eye of the Medusa's head borne by Perseus. It is the best known of the eclipsing binaries: these are mutually orbiting pairs of stars where the orbital plane is edge-on to our view, so that each star is seen to pass in front of the other. Algol is usually of magnitude 2.1, but drops to 3.4 and returns in the course of about ten hours every 2.86739 days. The brighter star is 3 times the size of the Sun, about four times its mass, and about 100 times its luminosity; it is a hot white star. The fainter companion is a cooler orange star of about the Sun's mass, but $3\frac{1}{2}$ times its diameter. The two bodies are separated by only $6\frac{1}{2}$ million miles. They are close enough to distort one another through tidal effects and probably have also exchanged material, another example of mutual evolutionary influence in binary stars. Gradual changes in the characteristics of the orbit suggested the presence of a third star, which was finally detected by regular changes in the Doppler shifts in the spectral lines. Algol C is a star of $1\frac{1}{2}$ times the mass of the Sun, orbiting the other two stars every 1.862 years at a distance of about fifty million miles. The entire stellar system lies 100 light-years away.

the Algol system



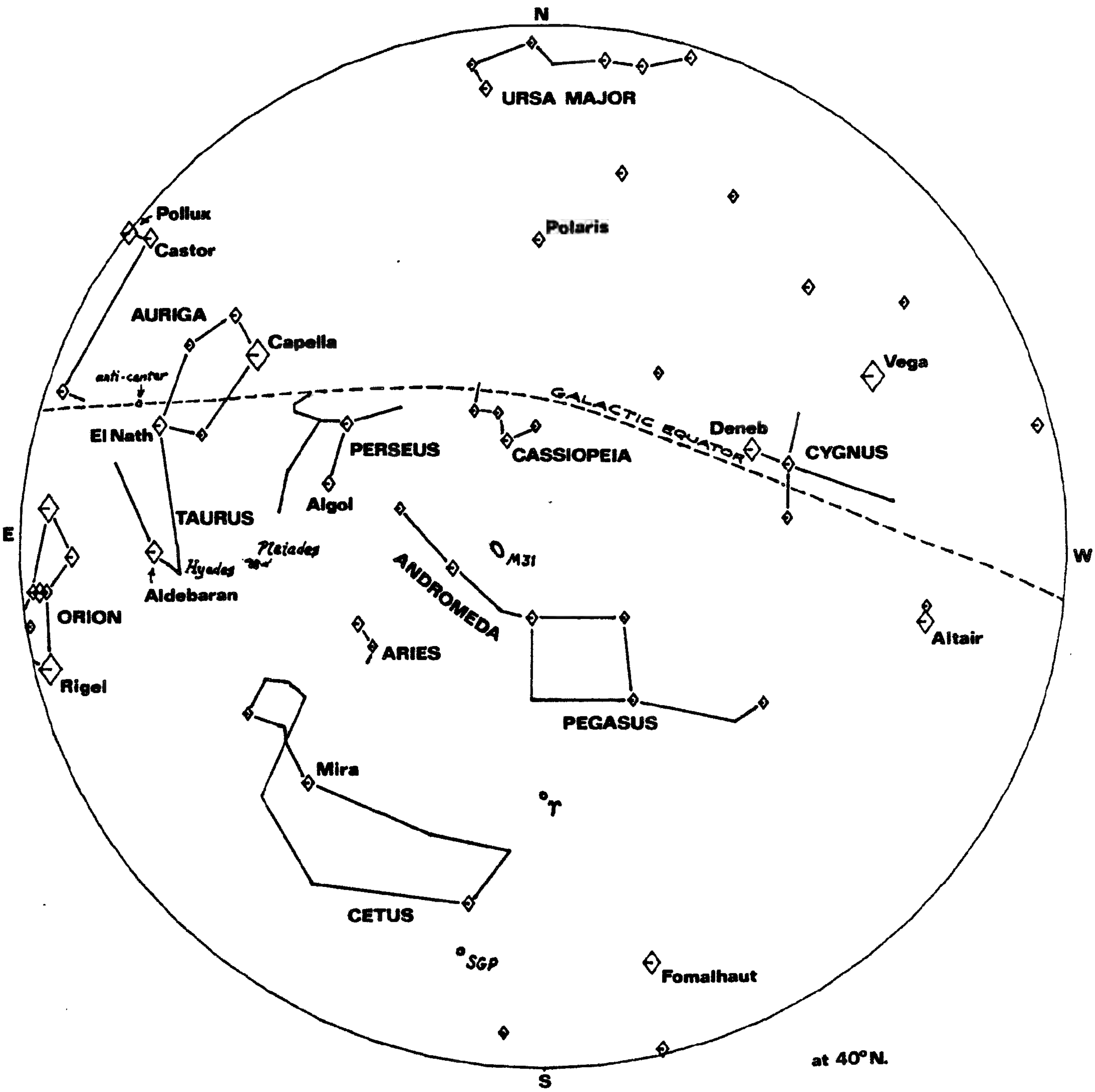
the view presented to us



The Sun-Earth system, for comparison; Earth is drawn about 50 times too large

We will leave this mythological group and return to the meridian, the north-south line, of the sky. *Polaris*, one of the most famous of all stars, is only the 49th brightest star, being of magnitude 2.0. It is not actually *at* the North Celestial Pole, but is just under 1° away and is the brightest star in that region. The precession of Earth's axis is carrying the Pole *toward* Polaris; in 2102, Polaris will be at its closest to the Pole, only $27\frac{1}{2}$' of arc away. This star is perhaps 360 light-years distant and so is about 1600 times as luminous as the Sun. It is slightly variable, with a period of 3.97 days and a range of 0.1 magnitude. One of the Great Embarrassing Moments in astronomy occurred when it was discovered that the light from Polaris, which had been used as a standard of comparison, wasn't constant. Polaris has a faint companion which is again only detectable from a study of the Doppler shift of the spectral lines (such stars are called *spectroscopic binaries*); the second star orbits with a period of 30.5 years at a distance of from 104 to 476 million miles.

Low in the south is found *Fomalhaut*, in Pisces Austrinus, the Southern Fish; the star's name derives from *Fum al Hūt*, "the Fish's Mouth." It was sometimes called "the Solitary One," as this bright star lies in a fairly empty part of the sky. It is another white star close at hand at 23 light-years' distance; it is about 14 times the Sun's luminosity and twice its size. A faint orange star of magnitude $6\frac{1}{2}$ follows Fomalhaut through space at a separation of about a light-year: they may be fellow members of a now-dispersed star cluster.



the sky at zero hours sidereal time

it appears as shown at: 12:20 AM local daylight time on 1 October

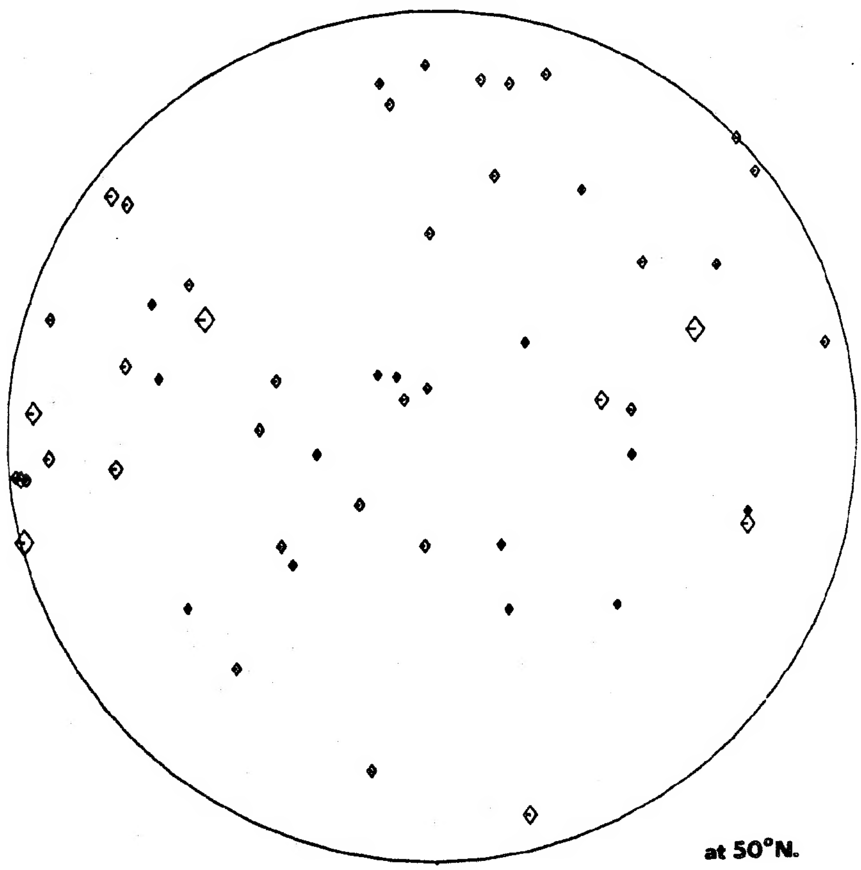
9:20 PM local standard time on 1 November

7:20 PM " " " on 1 December

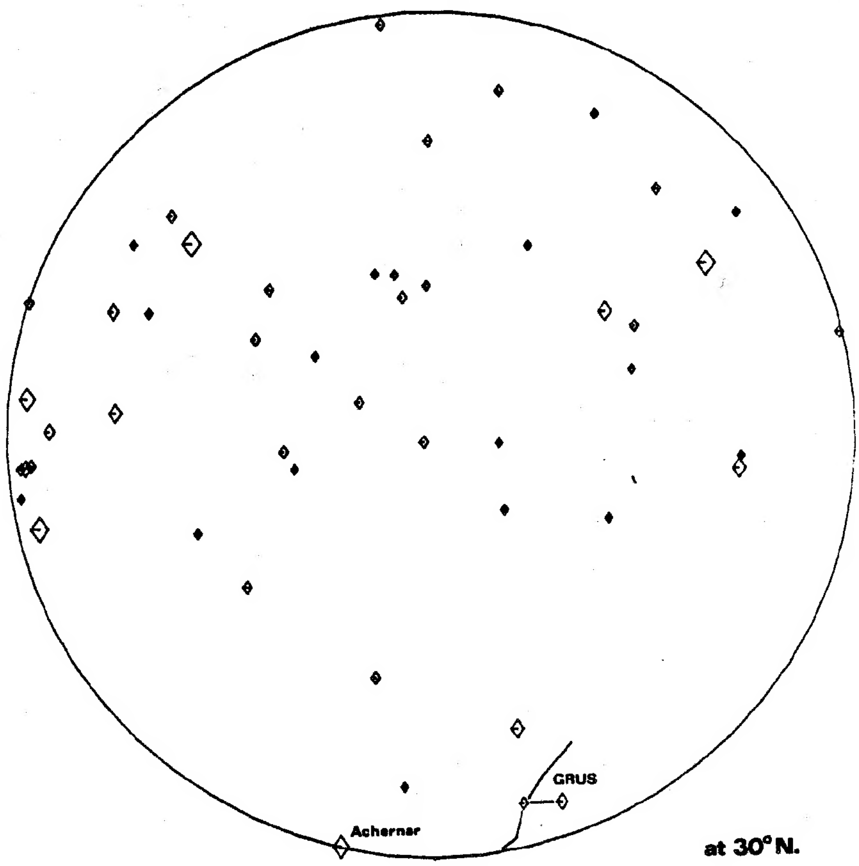
5:20 PM " " " on 1 January

♈ marks the location of the Vernal Equinox

SGP is the South Galactic Pole, the southern end of the Milky Way's axis of rotation



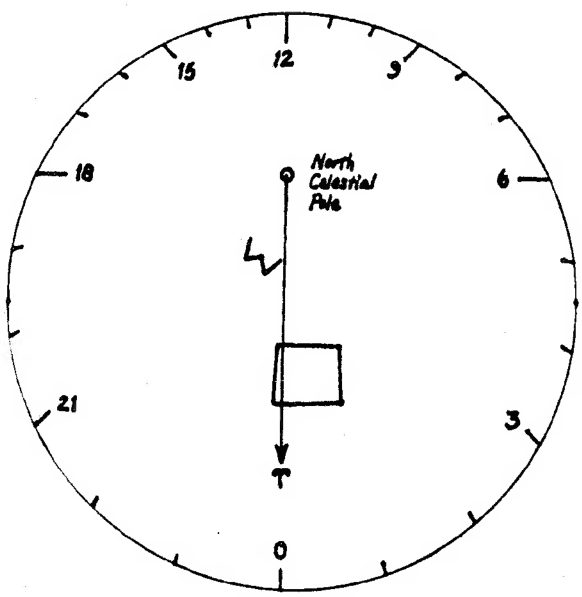
at 50°N.



at 30°N.

Aries is the Ram, which in one story was sacrified, after which its fleece was turned into gold, becoming the object of the Argonauts' quest. This was once the area where the Vernal Equinox stood some 2500 years ago, when classical astrology was formalized. Even today, the Vernal Equinox is still referred to as the First Point of Aries and is symbolized by the Ram's Head (♈). In the maps shown, the Vernal Equinox is on the meridian, making the time at zero hours sidereal time. Sidereal time is based on the actual period of Earth's rotation, which is 23 hours 56 minutes 4.091 seconds; the sidereal day is divided into 24 hours and is used by astronomers for the purpose of instrument pointing. An approximate sidereal clock can be imagined by drawing a line from Polaris south through the westernmost star in the "W" of Cassiopeia and through the eastern side of the Great Square of Pegasus. When that line points due south, it marks zero hours; it then cycles through a 24-hour clock, turning "counter-clockwise." The precession of the

a sidereal sky clock



Earth's axis has carried the Vernal Equinox westward to the boundary of the constellations Pisces and Aquarius. This is the origin of the phrase, "the dawning of the Age of Aquarius;" this Age will supposedly be marked by about 2000 years of peace and good fellowship for all humanity.

The large pentagon of stars marks *Auriga*, the Charioteer. This name appears to have been long associated with the constellation and probably descends from Babylonian times.

The bright star in Auriga is *Capella*, known as "the Little She-goat" since the age of Rome. It is the northernmost of the first-magnitude stars and is circumpolar (never setting) in the United States. Capella is about 45 light-years away and is another spectroscopic binary. The two stars are about 70 million miles apart and orbit one another in nearly circular paths with a period of 104.0 days. The brighter of the two is a yellow giant thrice the Sun's mass, 13 times its diameter, and 90 times its luminosity; the fainter one is a hotter, whitish star having 2.8 times the Sun's mass, 7 times its size, and 70 times its luminosity. The spectra of both stars are peculiar, again indicating that the two stars have affected the development of one another. This pair is, in turn, orbited by another binary about a sixth of a light-year away; the system is composed of two tiny red dwarf stars with a total luminosity about a hundredth as great as the Sun's. Capella is thus at least a quartenary stellar system.

Linked to Auriga at the star El Nath is *Taurus*, the Bull; it is generally depicted, though, as only the front half of a bull. It is believed to be one of the first constellations invented, as the Vernal Equinox passed through Taurus from 4000 to 1700 BC, considered the golden age of archaic astronomy.

Taurus consists of a "V" for the head of the bull and two long "horns" extending from the top of the "V." Marking one eye is the orange star *Aldebaran*, from *Al Dabaran*, "the Follower [of the Pleiades]." It is a so-called red giant star 40 times larger than the Sun and about 125 times as luminous. Aldebaran has a surface temperature of 3400 K (5700° F); it is slightly variable, with a range of about 0.15 magnitude. It is positioned 68 light-years from us. It appears to be accompanied by a 13th-magnitude red dwarf companion emitting a thousandth the Sun's energy; this tiny star is 650 times as far from Aldebaran as Earth is from the Sun.

El Nath obtains its name from *Al Nāṭiḥ*, "the Butting One," as it is at the tip of Taurus' northern horn. It is a giant star, white in color, at a distance of about 300 light-years, possessing about 1700 times the luminosity of the Sun.

The face of the Bull is a single grouping of stars in space called the *Hyades*, named for the seven daughters of Atlas and Aethra, half-sisters to the Pleiades. H.P. Lovecraft added to the mythology of this group in placing the present realm of the Old Ones at the Lake of Hali "on a dark star near Aldebaran in the Hyades." Aldebaran does not actually belong to this group, but happens to lie along our line of sight. The Hyades is classified as a galactic or open cluster, the center of which is 130 light-years away. Present stellar theory holds that such clusters consist of stars which all formed at about the same time from part of the same giant molecular cloud, a region of gas and dust which may be up to hundreds of light-years across. These open clusters do not have a high enough density of stars to remain gravitationally bound together: in the course of some hundreds of millions of years, the ejection of faster-moving members and the action of tidal forces imposed by the Galaxy will usually scatter such a cluster. The Sun was once a part of an open cluster early in its history; Time and Tide has long since melded its fellows into the Galaxy. The main part of the Hyades is spread across about 3½°, or a linear distance of about 8 light-years; it appears to be part of a much larger association known as the Taurus Moving Cluster, which is about ten times bigger (Capella may be a member!). There are 132 stars in the Hyades brighter than ninth-magnitude; all told, the cluster may have several hundred members. There are no stars in this cluster hotter than about 9000 K: stellar evolutionary theory tells us that the Hyades is thus about 400 million years old.

To the west of the Hyades, there is a smaller but more conspicuous asterism, called the *Pleiades*, also known as "the Seven Sisters." This is among the first of the constellations to be mentioned in astronomical literature, appearing in Chinese annals for the year 2357 BC, when the Vernal Equinox lay close to it. It was known to all ancient peoples and figures in stellar myths throughout the world. In the classical period, the Earth's axial precession had become recognized: the time for the cycle (25,800 years) was known as "the Great Year of the Pleiades." Some believe that the name may come from the daughters of Atlas and Pleione, who was transformed by Zeus into a flock of doves (*peleiades*) to escape Orion. Others suggest that it comes from the word *plein*, meaning "to sail," as the rising of this group with the Sun in May marked the beginning of the Mediterranean navigational season and its setting at sunrise in late autumn indicated the ending. The Pleiades are a galactic cluster like the Hyades. It lies about 410 light-years off, about three times further away; since it appears about a third as wide as the Hyades, it must be about the same linear diameter. The Pleiades possesses somewhere between 300 to 500 member stars. None of these is hotter than about 12,000 K (21,000° F), from which we infer that the cluster is about 20 million years old, very new in cosmic terms. In fact, some of the dust from the original cloud from which the stars formed is still present: wisps of nebulosity can be easily seen in small telescopes, reflecting the intense blue and violet light of the brighter stars. The astronomical designation of the Pleiades is M45.

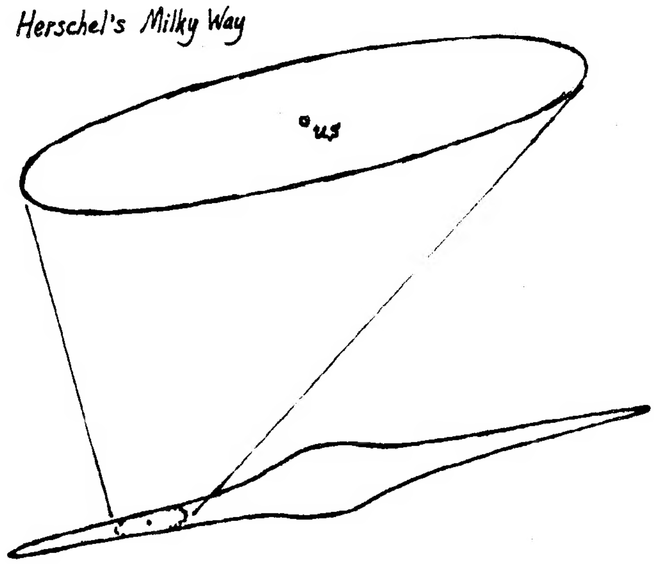
For observers in the southernmost United States, two other items might be mentioned. *Grus*, the Crane, protrudes from the southern horizon. This is a "modern" constellation, invented by Johann Bayer for his stellar atlas, the *Uranometria* of 1603.

Just visible at the horizon is *Achernar*, in Eridanus, the River, a constellation which wanders widely across the southern sky. The name of the star comes from *Al Āhir al Nahr*, "the End of the River." This is the 9th brightest star in the sky, although it may not appear so to American observers due to the thickness of atmosphere through which it must be viewed. Achernar is a hot, bluish star with a surface temperature of 14,000 K (25,000° F). It is seven times the size of the Sun and is about 650 times as luminous; it lies 120 light-years away from us.

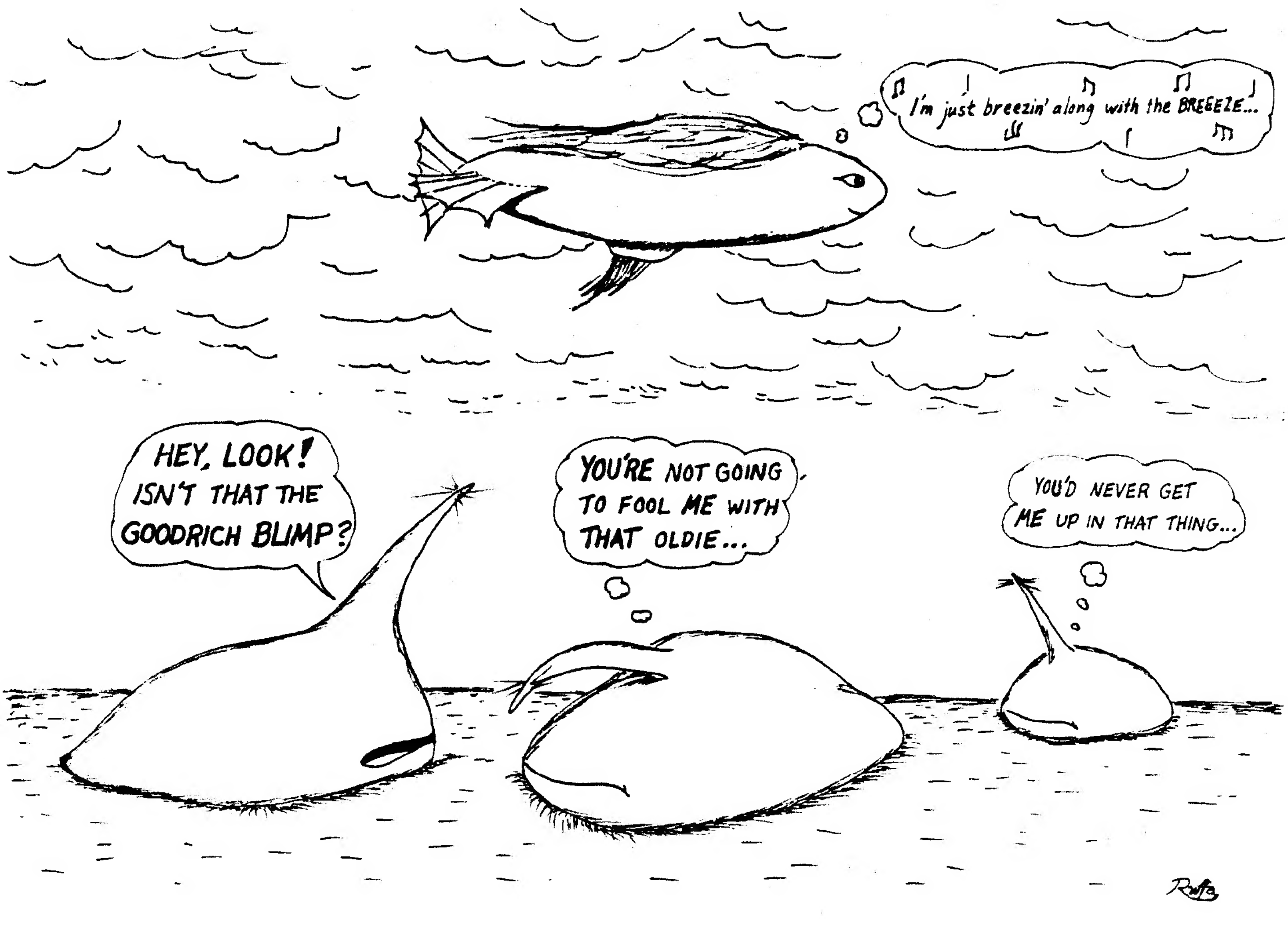
At this time of year, the band of the Milky Way stretches from the eastern to the western point on the horizon, passing nearly overhead. Astronomers place an imaginary line through the middle of the Galactic band, calling it the *Galactic Equator*. On this Equator, close to El Nath, is shown the *anti-center*, the point diametrically opposite to the direction of the center of the Galaxy. By looking again at the stars we have discussed, one is impressed by the fact that most of the bright stars lie near the Galactic Equator; those which do not are not more than a few hundred light-away away. One then quickly comes to the conclusion that we live in a *disk* of stars.

William Herschel of England (originally of Hannover) conducted telescopic surveys of the sky and made essentially the same deduction about two hundred years ago. He determined that the Milky Way was a disk about three thousand light-years in radius and less than a thousand light-years thick, with our Solar System at the Center (!). A similar view prevailed through the intervening time until 1930, when Robert Trumpler of the United States demonstrated the existence of interstellar *extinction*. He studied a number of galactic clusters, measuring their apparent size and the brightness of their stars. Trumpler found that the clusters became fainter faster than they became smaller. That is to say that, making the not entirely unreasonable assumption that all galactic clusters are the same linear diameter (true to within a factor of around five), these clusters looked farther away, to judge by their brightnesses, than one would imagine by their apparent sizes. This is the sort of phenomenon one experiences in a fog, where various objects seem farther away than they actually are and where there is a limit to the distance that one may see at all (the "visibility"). In the Galaxy, this "fog" is provided by the countless tiny grains of carbon, silicon, and all manner of metals scattered through interstellar space. Even with large telescopes, it is difficult to see deeper into the Galaxy than about 10,000 light-years within the disk. Various lines of evidence made clear by 1935 that we live in a spiral galaxy some 100,000 light-years across, about 28,000 light-years out from the center and very nearly on the plane of symmetry.

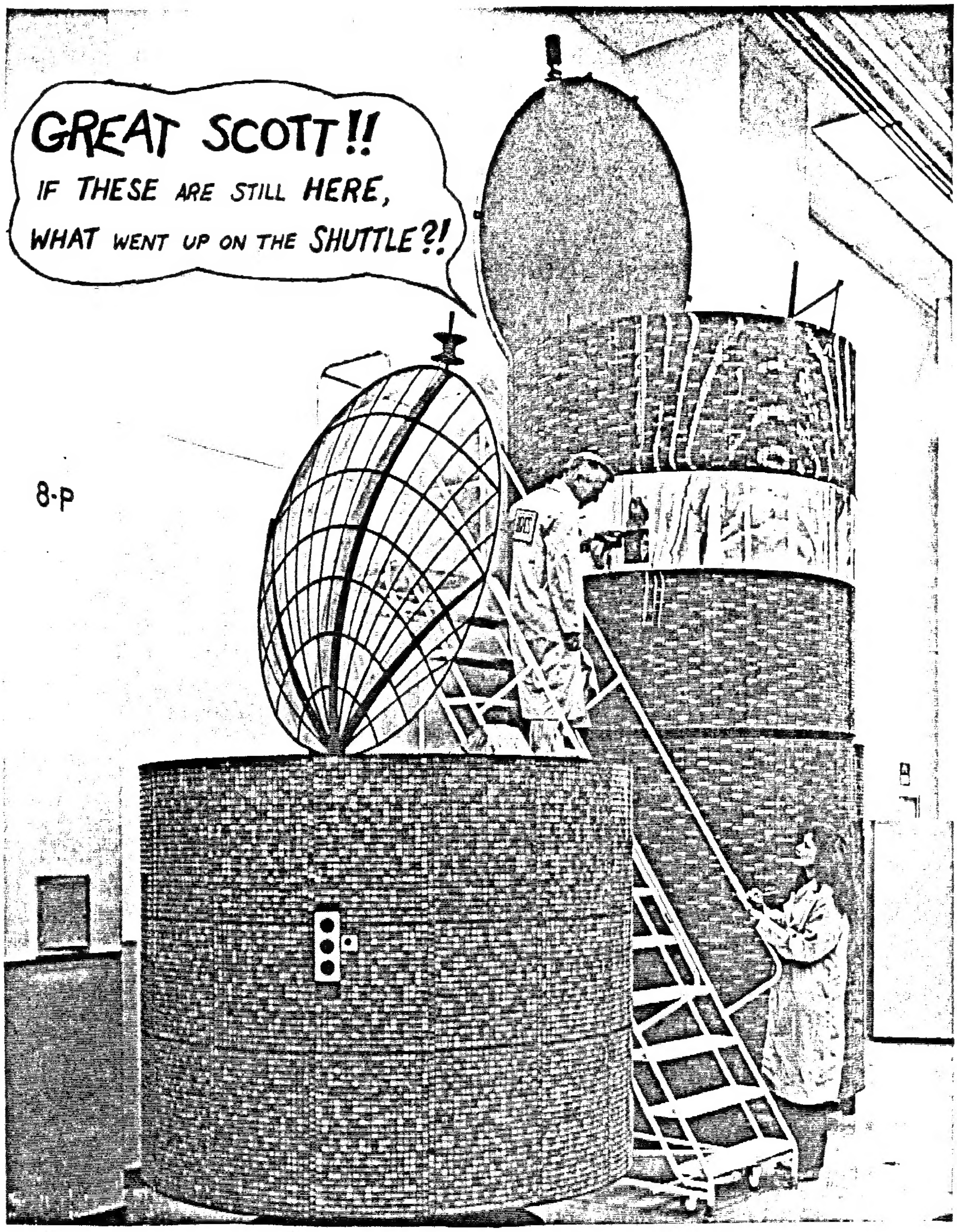
edge-on views

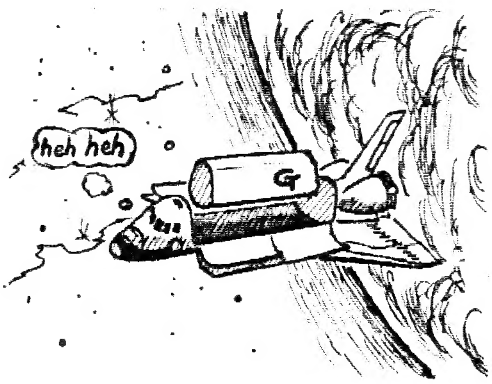


the "modern" Galaxy, one of 100 billion



Meanwhile, at the Hughes High-bay...





AstroTechnics (PyroTechnics 34)

a production of the Center for Spaced Research

GENERAL TECHNICS